THE APPLICATION OF TRACE ELEMENT GEOCHEMISTRY TO DETERMINE THE PROVENANCE OF SOAPSTONE VESSELS FROM DORSET PALAEOESKIMO SITES IN WESTERN NEWFOUNDLAND

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THE APPLICATION OF TRACE ELEMENT GEOCHEMISTRY TO DETERMINE THE PROVENANCE OF SOAPSTONE VESSELS FROM DORSET PALAEOESKIMO SITES IN WESTERN NEWFOUNDLAND

By

Cynthia Marie O'Driscoll

A Thesis submitted in partial fulfilment of the requirements for the degree of
Master of Arts

Department of Anthropology
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ABSTRACT

Petrography and trace element geochemistry are used to characterise Dorset Palaeoeskimo (ca. 2000-1200 B.P.) soapstone artifacts from five sites in Western Newfoundland. Soapstone artifacts were collected from Cape Ray, Englee, Fleur de Lys, Pittman, and Port au Choix sites, and their mineralogy and trace element abundances are compared to outcrop samples from Bear Cove Road, Fleur de Lys, St. Anthony, Straitsview, Tablelands and Trout River. Complementary analytical techniques were used to characterise all forty-four samples. Petrographic analysis was supplemented by x-ray diffraction analysis to identify mineralogy, major element determinations were made by x-ray fluorescence, and trace elements were determined using inductively coupled plasma-mass spectrometry.

Immobile or alteration resistant elements are the most useful elements for determining provenance. For this study, these are the rare earth elements (REE) and the high field strength elements niobium and thorium. The REEs are a coherent group of elements and exhibit certain behaviours as a group. Differences in the REE chemistry of samples are based on REE abundances, the shape of the REE patterns and the slopes of the REE pattern when plotted on a log-scale plot where concentrations of these elements are normalised to standard values for primitive mantle. Definite differences exist between REE abundances in the tested samples. There are however, consistent thorium and light rare earth element enrichments, and a negative niobium anomaly in most artifacts, and in the Tablelands and Trout River outcrop samples. Patterns are characterised as U-shaped, L-shaped, or linear.

It is possible to define sub-populations of artifacts based on individual and group rare earth element concentrations and patterns. Sample populations from the Fleur de Lys outcrop match artifacts collected at Englee, Fleur de Lys, and the Pittman site suggesting Dorset groups at these sites collected rocks at the Fleur de Lys quarry. The artifacts from Cape Ray and Port au Choix have not been significantly carbonatised and have higher concentrations of aluminium represented as chlorite in thin section, and only 10-15% carbonate (i.e., magnesite). However, Cape Ray and Port au Choix artifacts have significant differences in REE (especially heavy rare earth elements) abundances and their different shaped REE patterns suggest different outcrop sources. This differs from the significantly carbonatised (i.e., 40-50% magnesite in thin section) artifacts from Englee, Fleur de Lys, and the Pittman site. These artifacts exhibit more intensive alteration and have similarly shaped REE patterns and abundances.

Of the outcrop samples tested, only Fleur de Lys is suggested to be a possible source of artifacts. The St. Anthony outcrop (based on enriched heavy REE abundances) is clearly derived from a different mantle source than the Trout River and Tablelands samples, which exhibit enriched Th and have a negative Nb anomaly and very low REE concentrations. The Straitsview outcrop is not of ultramafic composition and is not a source of artifacts studied.

These data have notable consequences for the distribution of soapstone during the Dorset period in Newfoundland, and support Douglas Robbins's theory, which states that three regional cultural variants of the Dorset culture occur in Newfoundland; the west coast (e.g., Port au Choix), northwest coast (e.g., Fleur de Lys, Pittman, and Englee sites) and south coast (e.g., Cape Ray) variants. This hypothesis is based on the idea that the Dorset utilised the local raw materials within these particular regions.

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This thesis is dedicated to my parents, who provide constant support to me in my endeavours.

TABLE OF CONTENTS

Page
ABSTRACT ii
ACKNOWLEDGEMENTS v
TABLE OF CONTENTS vi
LIST OF FIGURES ix
LIST OF TABLES xi

CHAPTER ONE: INTRODUCTION

1.1 Scope of Thesis 1
1.2 Regional Setting 4
1.3 Soapstone in Prehistory 6
1.4 Soapstone Quarry Technology 12
1.5 Provenance Studies of Soapstone 16
1.6 Present Investigation: Sampling Procedure and Methodology 19

CHAPTER TWO: DESCRIPTION OF DORSET SITES AND ARTIFACT ASSEMBLAGES FROM WEST NEWFOUNDLAND

2.1 Introduction 22
2.2 Classification and Mineralogy of Ultramafic Rocks 22
2.3 Site and Artifact Descriptions 23
2.3.1 Cape Ray 23
2.3.1.1 Petrographic Observations 26
2.3.2 Englee 28
2.3.2.1 Petrographic Observations 29
2.3.3 Fleur de Lys 31
2.3.3.1 Petrographic Observations 33
2.3.4 Pittman Site 33
2.3.4.1 Petrographic Observations 36
2.3.5 Phillip's Garden, Port au Choix 37
2.3.5.1 Petrographic Observations 39
2.4 Summary of Chapter Two 39

CHAPTER THREE: DESCRIPTION OF GEOLOGICAL UNITS

3.1 Introduction 43
3.2 General Framework 43
3.3 Chemical and Physical Processes 45
3.2.1 Metamorphism, Serpentinisation, and Carbonatisation 45
3.3 Outcrop Study Areas and the Geology of Western Newfoundland 47
3.3.1 Baie Verte Peninsula 48
3.3.1.1 Unit Description 50
3.3.2 St. Anthony (Howe Harbour) Outcrop 50
3.3.2.1 Unit Description and Petrography 54
3.3.3 Trout River (Gros Morne National Park) 56
3.3.3.1 Unit Description 58
3.4 Summary of Chapter Three 58

CHAPTER FOUR: BULK ROCK AND TRACE ELEMENT GEOCHEMISTRY

4.1.1 Introduction 61
4.2 Rationale for Geochemical Applications and Data Quality Assessment 61
4.3 Trace Elements 62
4.4 Explanation of Geochemical Plots 64
4.4.1 Major Element Plots to Distinguish Rock Units 64
4.4.2 Extended Rare Earth Element Geochemistry 73
4.4.2.1 A Comparison of REE Patterns in Artifacts Versus Outcrops 77
4.4.2.2 A Comparison of REE Patterns Between Fleur de Lys Artifacts and Artifacts from other sites 84
4.4.2.3 A Comparison of REE Patterns of Different Outcrops 88
4.6 Summary of Results 91

CHAPTER FIVE: DISCUSSION OF FINDINGS AND CONCLUSION

5.1 Introduction 99
5.2 Discussion of Fleur de Lys Artifact and Outcrop Samples 99
5.3 A Summary of the Main Petrological and Geochemical Characteristics of the Artifacts and Outcrops 101
5.4 Multiple Soapstone Sources and Sub-Populations of Artifacts 104
5.5 Who Utilised the Fleur de Lys Quarry? 106
5.5.1 Theories of Soapstone Exchange 106

5.6 If not from Fleur de Lys, then where? 108
5.7 Robbins's Regional Variants Theory 110
5.8 The Advantages of Using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) over Instrumental Neutron Activation Analysis (INAA) for Characterising Soapstone Artifacts 112
5.9 Observations and Challenges of this Study 114
5.10 Conclusion 116

ABBREVIATIONS

ICP-MS: Inductively coupled plasma – mass spectrometry
INAA: Instrumental neutron activation analysis
IUGS: International Union of Geological Sciences
ppb: parts per billion
ppm: parts per million
REEs: Rare earth elements
RNAA: Radiochemical separation neutron activation analysis
XRD: X-ray diffraction
XRF: X-ray fluorescence

REFERENCES CITED 120

APPENDIX ONE

Petrography A1-1

APPENDIX TWO

Major and Trace Element Analyses A2-1

APPENDIX THREE

Geological Timescale A3-1

APPENDIX FOUR

Glossary of Terms A4-1

LIST OF FIGURES

Page

Figure 1.1: Tectonic Divisions of the Island of Newfoundland 5
Figure 1.2: Artifact Sites Sampled 7
Figure 1.3: Outcrop Sampling Locations 8
Figure 1.4: Dorset Soapstone Cooking Pot 10
Figure 1.5: Dorset Soapstone Lamp 10
Figure 1.6: Schematic of Sampling Procedure and Methodology 20

Figure 2.1: Mineralogy of Parent and Altered Ultramafic Rocks 24
Figure 2.2: Cape Ray Artifact CjBt-1:3121 27
Figure 2.3: Photomicrograph of Artifact CjBt-1:2896 from the Cape Ray Site 27
Figure 2.4: Englee Artifact EeBa-1:697 30
Figure 2.5: Fleur de Lys Quarry Localities 1-6 32
Figure 2.6: Fleur de Lys Artifact EeBa-1:826 36
Figure 2.7: Pittman Site Artifact DkBe-1:1019 36
Figure 2.8: Photomicrograph of Artifact EaBa-1:826 from Fleur de Lys 35
Figure 2.9: Photomicrograph of Artifact EaBa-1:1661 from Fleur de Lys 35
Figure 2.10: Photomicrograph of Artifact DkBe-1:1019 from the Pittman Site 38
Figure 2.11: Photomicrograph of Artifact DkBe-1:1020 from the Pittman Site 38
Figure 2.12: Port au Choix Artifact EeBi-1:4833 40
Figure 2.13: Photomicrograph of Artifact EeBi-1:14128 from Port au Choix 40

Figure 3.1: Outcrop Sampling Areas for this Study 44
Figure 3.2: The Major Zones of the Island of Newfoundland 59
Figure 3.3: Large Talc Grain 51
Figure 3.4: Photomicrograph of Outcrop Sample FDL-1 from the Fleur de Lys Quarry, Locality 1. 52
Figure 3.5: Photomicrograph of Outcrop Sample FDL-4 from the Fleur de Lys Quarry, Locality 1. 52
Figure 3.6: Photomicrograph of Outcrop Sample Anth 3 from St. Anthony 55
Figure 3.7: The Tablelands Outcrop 57
Figure 3.8: Outcrop sample TR2 from Trout River Outcrop 58

Figure 4.1: Ternary Diagram of Major Elements Cr-Al_2O_3-MgO of Artifacts 66
Figure 4.2: Ternary Diagram of Major Elements Cr-Al_2O_3-MgO of Outcrop Samples 67
Figure 4.3: Artifact Symbols 68
Figure 4.4: MgO-Ni-Sr of Artifacts 69

Figure 4.5: MgO-Ni-Sr of Outcrop Samples 71
Figure 4.6a: LOI-Sr of Artifacts 72
Figure 4.6b: LOI-Sr of Outcrops 72
Figure 4.7: LOI-SiO_2 of Fleur de Lys Artifacts and Outcrop Samples 74
Figure 4.8: La/Lu vs MgO Artifacts 75
Figure 4.9: REE Diagram of Cape Ray Artifacts versus Fleur de Lys Outcrop Samples 78
Figure 4.10: REE Diagram of Englee Artifacts versus Fleur de Lys Outcrop Samples 79
Figure 4.11: REE Diagram of Fleur de Lys Artifacts versus Fleur de Lys Outcrop Samples 81
Figure 4.12: REE Diagram of Pittman Artifacts versus Fleur de Lys Outcrop Samples 82
Figure 4.13: REE Diagram of Port au Choix Artifacts versus Fleur de Lys Outcrop Samples 83
Figure 4.14: REE Diagram of Englee versus Fleur de Lys Artifacts 85
Figure 4.15: REE Diagram of Pittman versus Fleur de Lys Artifacts 86
Figure 4.16: REE Diagram of Port au Choix versus Fleur de Lys Artifacts 87
Figure 4.17: A Comparison of REE Concentrations of Straitsview and Fleur de Lys Outcrops 89
Figure 4.18: REE Diagram of all Outcrop Samples versus Fleur de Lys Outcrop Samples 90

Figure 5.1: A Comparison of Instrumental Neutron Activation Analysis (INAA) Limits of Detection, and Inductively Coupled Plasma – Mass Spectometry Detection Limits from Jenner (1990) and from this Study (2000). 113

Figure A2-1: Precision of the Dunite standard DTS-1 from Five Different ICP-MS Runs A2-5

LIST OF TABLES

Page

Table 4.1: Geochemical Data for Artifacts 92

Table 4.2: Geochemical Data for Outcrop Samples 97

Table A2-1: Comparison of Dunite Standard DTS-1 from Four ICP Runs A2-4

Table A2-2: Concentration for Each Sample by Individual Run A2-9

CHAPTER ONE

INTRODUCTION

1.1 Scope of Thesis

The Dorset Palaeoeskimo are an Arctic Small Tool Tradition (ASTt) culture that migrated from the western arctic to the eastern Canadian arctic and Greenland by 4,000 B.P. (before present), and south into Newfoundland by 1,900 B.P. (Dumond 1987). The last evidence of the Dorset is found in Northern Labrador and Ungava approximately 500 years ago (Tuck 1976). Temporally, the Dorset are the last Palaeoeskimo culture to inhabit Canada and Greenland and follow Independence I, Sarqaq, Pre-Dorset, Independence II, and Groswater Palaeoeskimos, respectively. The Neoeskimos (Thule), who are the ancestors of the modern day Inuit, replace the Palaeoeskimos; however the relationship between these two groups has not yet been clearly determined (McGhee 1996).

The Dorset culture is represented in the Canadian arctic and subarctic archaeological record by a stone and bone tool technology that reflects a maritime-adapted, hunting and gathering subsistence strategy. The Dorset used specialised tools to maintain their marine-oriented lifestyle and a variety of lithic raw materials were employed in tool production. The typical Dorset tool assemblage consists of harpoon heads made from bone and burin-like tools, microblades, projectile points, and scrapers made of various types of chert, and lamps and cooking vessels made from soapstone. Soapstone outcrops are common in the arctic and eastern subarctic regions of Canada and it logically follows that the lithic raw materials utilised by the Dorset originated from sources in these areas. In particular, soapstone outcrops located in Labrador and Newfoundland probably equipped the Dorset in these areas with the soapstone material they required.

In 1985 Douglas Robbins suggested that there were three regional variants of the Dorset culture in Newfoundland, namely, the west coast, northeast coast, and south coast populations (Robbins 1985). These population variants are manifested in the archaeological record by differences in tool morphology and raw material. Sylvie LeBlanc (2000) investigates this rationale for Dorset sites in eastern Newfoundland based on artifact assemblages from Dildo Island and Saint-Pierre and Miquelon. Dorset endblades, scrapers, and microblades can be used to illustrate geographic uniqueness; however, in LeBlanc's (2000) preliminary synopsis endblades are used exclusively to illustrate regional variability. For example, variation of endblades exists in tool length, tool width, colour and quality of the chert, and the degree of workmanship, which in turn serves to distinguish regional groups. Another study, by John Erwin (2000), uses endblades from twenty-four Dorset sites in northeast Newfoundland to lend support to the regional hypothesis. Endblade morphology at these sites is fairly consistent (Erwin 2000). Erwin (2000) further suggests that the soapstone at Fleur de Lys might have a similar distribution, that is, within northeast Newfoundland.

A preliminary provenance study of soapstone by the author (O'Driscoll 1998) using x-ray diffraction (XRD) to characterise the mineralogy of soapstone artifacts from Cape Ray and samples from the Fleur de Lys soapstone quarry, provides evidence that the Cape Ray Dorset obtained their soapstone locally, or at least did not travel long distances to acquire it.

This thesis research evolved out of the geographically-limited study cited above. The goals of this study are to investigate the idea of regional expressions of the Dorset culture using sensitive and robust quantitative analytical techniques, namely, x-ray fluorescence (XRF) and inductively coupled plasma-mass spectrometry (ICP-MS). By determining the geological source of soapstone artifacts from five Dorset sites in western Newfoundland using XRF and ICP-MS, it is possible to explore Robbins' (1985) regional hypothesis by tracing the distribution of soapstone and thus revealing whether or not soapstone is an indicator of regional distinctiveness at Dorset sites in western Newfoundland.

Another component of this thesis is the investigation of the alteration process(es) of soapstone from a peridotite parent (or protolith)[1]. Metamorphism, serpentinisation, and carbonatisation have changed the primary mineralogy of the parent rock from olivine, pyroxene, spinel-dominated to a secondary assemblage consisting of serpentine, talc, and carbonate minerals. The extensive alteration resulting from these dynamic processes has also changed the relative abundances of rare earth elements (REEs) in these rocks and presents challenges to geochemically characterising individual rock assemblages. Immobile elements or elements that have resisted the effects of alteration are used to geochemically fingerprint the samples in an effort to define the source of artifacts or sets of artifacts. One aim of this study then, is to obtain consistent and reliable data that

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[1] Relevant geological terms are defined in Appendix Four.

characterises these rocks to determine the source(s) of the Dorset artifacts despite the limitations imposed by the inherent and complicated alteration history of soapstone.

The remainder of this chapter briefly describes the study area and sets up the cultural framework of this thesis. Chapter Two is an overview of the Dorset culture in Newfoundland and the Dorset sites from which the artifacts for this research were sampled. The petrography of the artifacts is also presented. Chapter Three contains the rock unit descriptions of the sampled outcrops and petrography. Chapter Four is a review of the geochemistry and includes a presentation of the trace element data.

This provenance study has significant cultural implications for the Dorset in west Newfoundland, interpreted here as the Great Northern Peninsula and the Baie Verte Peninsula. By tracing soapstone artifacts back to their geological source it is possible to determine the distribution of soapstone in west Newfoundland during the Dorset period. This has further ramifications for our understanding of Dorset groups on the island, particularly where and how far they were travelling to obtain soapstone. An interpretation of the data, discussion, and an investigation of Robbins' regional hypothesis are presented in Chapter Five.

1.2 Regional Setting

The geographic scope of this thesis is restricted to western Newfoundland. Tectonic divisions of the island of Newfoundland in this area are the Humber Zone and the western part of the Dunnage Zone (Fig.1.1). These zones have different geological origins, a result of tectonic events that formed Newfoundland; the Humber Zone

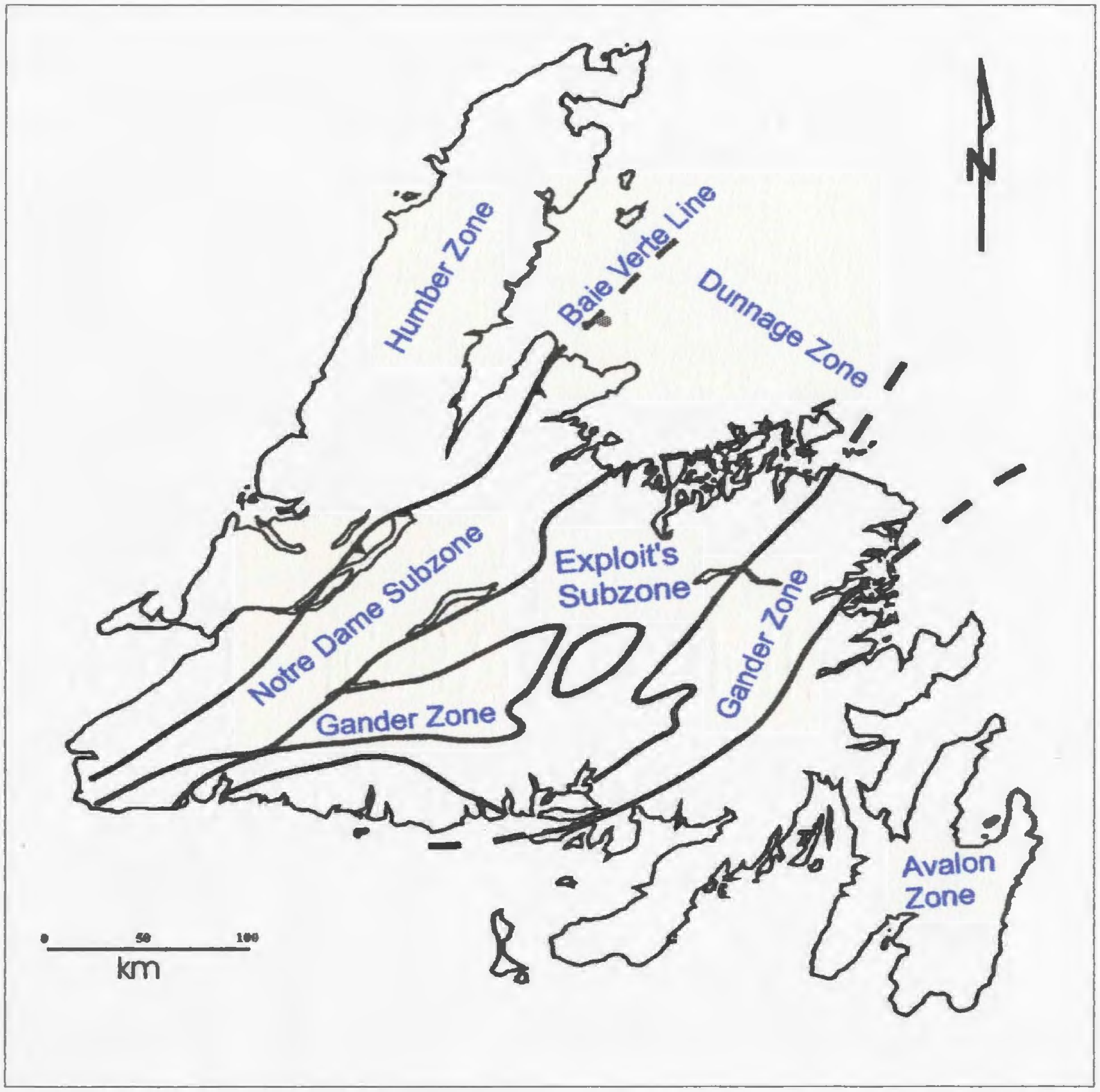


Figure 1.1: The Tectonic Zones of the Island of Newfoundland (adapted from Williams et al. 1988).

originally being the continental margin of ancient North America and the Dunnage Zone being composed of rocks that formed in the ancient Iapetus Ocean. The collision of these two zones formed the northern extent of the Appalachian Mountains. These specific areas were chosen for this research based on significant archaeological resources and the geological outcrops present within these zones.

Soapstone from prolific Dorset sites at Cape Ray, Englee, Fleur de Lys, the Pittman site, and Port au Choix were chosen from collections at the Newfoundland Museum (Fig.1.2). The Dorset soapstone quarry at Fleur de Lys and peridotite/harzburgite outcrops in western Newfoundland at Bear Cove Road, St. Anthony, Tablelands, and Trout River, were sampled in this study (Fig.1.3). A sample was taken from the Straitsview (Spillar's Cove) outcrop on the advice of a local resident who suggested, based on local folklore, that this outcrop was exploited by prehistoric groups.

1.3 Soapstone in Prehistory

Soapstone was an important material used by many prehistoric groups in North America, particularly for cultures inhabiting the Canadian arctic and subarctic. It is durable, easily malleable, has insulating properties, and is repaired easily if broken. These characteristics make soapstone an ideal material for the construction of lamps and cooking pots. Lamps and cooking vessels must be constructed of a strong material to enable daily usage. Soapstone has also been used to depict spiritual and symbolic forms in prehistoric and historic times (e.g., Dumond 1987; McGhee 1996; Thomson 1985);

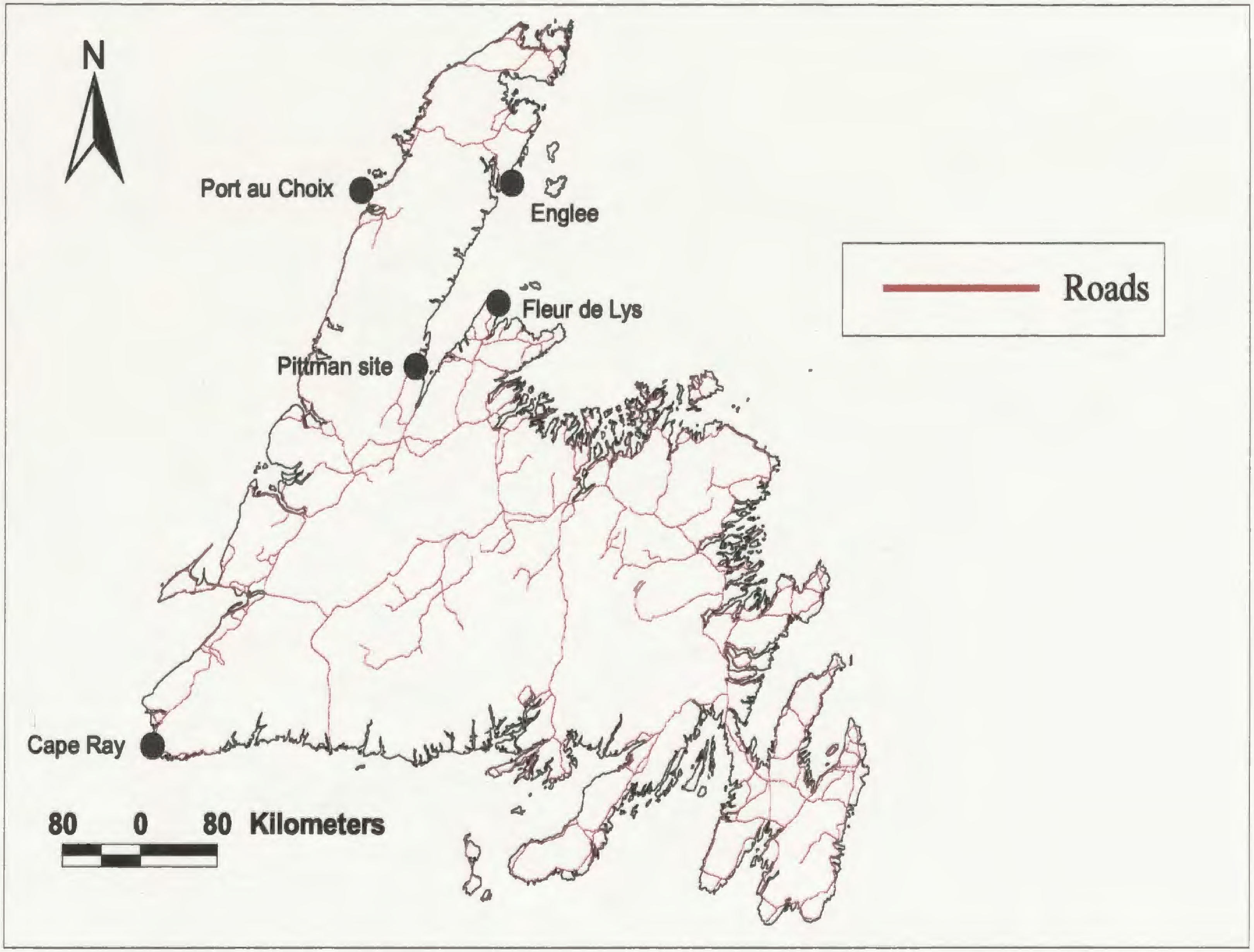


Figure 1.2: Artifact sample sites (Source: ArcView 3.2. Created in the QEII Map Library)

Figure 1.3: Outcrop sampling locations (Source: ArcView 3.2, Created in the QEII Map Library)

however these artifacts are most commonly found at sites in the arctic and will not be investigated here.

For certain Palaeoeskimo groups in the north and Archaic groups in the eastern United States (see below), soapstone vessels were constructed for cooking and lighting purposes. The soapstone was obtained locally, through seasonal expeditions, or through trade with neighbouring groups. Analyses of quarries, quarrying tools, and soapstone vessels, along with information on protohistoric and historic groups who also used soapstone in the same regions, are used to infer quarrying behaviour and soapstone tool function.

Cooking vessels were either used in conjunction with lamps, often suspended above them, or alone. Dorset cooking pots are usually rectangular or square and have angular sides that measure more than 90 degrees perpendicular to the base (de Laguna 1940:62; Linnamae 1975; Fig.1.4). Side and base thickness are variable and may reflect the quality of the soapstone or cultural preferences. Vessels often have adherring fuel on both the interior and exterior. A charred exterior was likely a result of flame exposure and in many cases the burned organic residues on the inside of the vessel are thought to be the remnants of seal oil or other food remains.

The "Eskimo" lived in a very harsh environment and the "need for warmth and light [was] only second to the prime need for food." (Hough 1898:1027). It is not surprising then that soapstone lamps were important components of prehistoric Dorset culture and were used for 2,000 years in the Arctic (McGhee 1984:372). Centuries later,

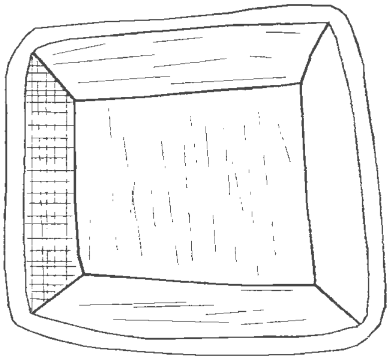


Figure 1.4: Dorset soapstone pot (schematic after de Laguna 1940).

Figure 1.5: Dorset soapstone lamp from the Bird Cove site, Great Northern Peninsula, Newfoundland (Courtesy of Tim Rast).

the early Thule and historic Inuit still preferred soapstone to other, more convenient, materials for constructing lamps and often lengthy expeditions were organised to acquire this material (Hough 1898:1031; McGhee 1984:372). Although soapstone vessel form changed significantly over time, soapstone was still the main choice of raw material for the construction of vessels for the Dorset as well as for the Thule culture (McGhee 1984:372).

Dorset lamps, as indicated by lack of decorative elements, were likely used exclusively for functional purposes. Heat, light, drying clothes, and melting snow for drinking water are all probable functions of stone lamps (Hough 1898:1028). Lamps were often placed beneath overhanging soapstone pots for cooking. Boas (1964:136) describes a Central Eskimo fireplace where a blubber-ignited soapstone lamp and suspended pot are positioned next to a bed. The wick was trimmed continuously to ensure that the lamp didn't emit smoke, and a "trimmer" (bone, stone, or wooden segment) was used to maintain the proper wick length (Boas 1964; Hough 1898:1034).

Lamp form varies throughout arctic and subarctic North America. Hough (1898:1040) suggests that lamps from higher arctic latitudes are more specialised morphologically than lamps from lower latitudes. These are differentiated by different wick edge widths of lamps from southern Alaska and north Greenland. Lamp distribution throughout the Arctic regions of North America extends across arctic North America and then dips south to southern Labrador and Newfoundland, where the southernmost extent of the Dorset are recorded. Hough (1898:1040) connects the presence of stone lamps in Labrador to isotherms and thus low surface temperatures, which necessitate the use of lamps there. De Laguna (1940:53) suggests that Hough's criteria for explaining soapstone lamp form (i.e., temperatures, wick length) are indirectly related to shape, while function is probably the primary determinant of vessel shape, regardless of the raw material used. Soapstone lamps from southwest Alaska attributed to the Dorset culture are pear or elliptical in shape (de Laguna 1940:56; Fig.1.5). Lamp form also changed over time, from pear- or oval-shaped to semi-circular within Dorset culture (de Laguna 1940:60). Maxwell (1984:365) describes an evolution of Dorset lamps in the eastern arctic from rectangular during early Dorset to shallow and oval during later Dorset periods. Whether shape and form of lamps and cooking pots are an indication of cultural preferences or distinct cultural signatures has not been investigated satisfactorily.

In Newfoundland the presence of soapstone lamps is rare, other than some examples from Port au Choix and small, deep varieties from Fleur de Lys. Was this due to a more favourable climate, where warmth from lamps was not as critical or are some of the soapstone fragments recovered, presently interpreted as cooking pots, actually lamps? Only further examinations of current and past artifact collections can help answer this question.

1.4 Soapstone Quarry Technology

In prehistory, soapstone was quarried from outcrops throughout North America, particularly eastern North America. Outcrops are located throughout the Canadian Arctic including western Ungava Bay (Plumet 1980), along the Appalachian Mountain System from Newfoundland (Nagle 1984) to Alabama (Wright 1974) including Georgia, Virginia (Bushnell 1939), New England (Fowler 1945,1947,1966; Ward and Custer 1988), Maryland (Wilkins 1962), North and South Carolina (Heizer 1950; Holmes 1992; Luckenbach et al. 1975a&b; Overton 1969), Pennsylvania (Crozier 1939), and Washington D.C. (Holmes 1890). Quarries are also located in California (Schumacher 1878), and Wyoming (Frison 1982). Generally outcrops in Canada were utilised by Palaeoeskimos rather than Indian groups.

In 1897, William Henry Holmes published a comprehensive review of soapstone quarries and quarrying implements in the states of Maryland, Virginia, and Washington, D.C. (Holmes 1992). This publication was one of the first intensive compilations of prehistoric soapstone quarrying in North America and it continues to be an important source of information on prehistoric soapstone quarrying in the United States. Since Holmes' endeavours, soapstone is discussed mainly in cultural terms and only occasional publications have discussed the application of scientific methodologies to archaeology. With the advent of innovative analytical approaches that use semi-quantitative and quantitative techniques from other disciplines to examine archaeological materials, archaeological research has expanded into previously unexplored territory. These procedures provide new ways to investigate old research questions. For soapstone research, provenance studies and investigations of prehistoric quarrying and quarrying implements are directly related to questions of raw material distribution, trade, and exchange, as well as production sequences.

Since the 1940s, analyses of quarry technology have increased as quarrying tools have been recovered in larger numbers at archaeological sites in eastern Canada and the northeastern United States. Descriptions and interpretations of the function of these tools elucidate the variety of tools and stages of soapstone quarrying at the site where they have been recovered (e.g., Erwin 2000; Pottle 1998). Quarrying tools are often divided into categories based on the manufacturing stage for which they were thought to be used. At Fleur de Lys, Nagle (1982:116-118) proposed a quarrying model that has since been modified by Erwin (2001). Erwin's (2001) "four-stage reduction and finishing tool model" is based on the use of locally-derived sandstone quarrying tools recovered at Fleur de Lys. The initial extraction stage of the quarrying process required larger, crude tools for delineating the amount of material to be removed from the outcrop, typically measuring 50 cm x 50 cm at Fleur de Lys. The second stage employed long, rectangular-shaped, pointed implements to deepen the groove around the block or preform. Pecking tools, as evidenced by linear pecking marks on buried and unweathered soapstone, were used to reduce the soapstone still attached to the outcrop until a final impact would sever the soapstone preform from the quarry. Small, precise tools were used in the last stage, for gouging the centre of the vessel and carving the implement into the desired form. Evidence of finishing tools such as linear flakes and small incising tools at Fleur de Lys suggest at least some soapstone preforms were finished at the quarry, reducing the weight of the stone for travel and/or for use at the site.

The actual removal of the soapstone blocks or preforms from the outcrop required specialised techniques that perhaps Dorset and other prehistoric groups to the south developed in response to localised quarry conditions. For example, soapstone vessels quarried from the Rose Hill Quarry in Washington D.C. were very wide, which likely indicates they were not undercut during quarrying (Holmes 1890:324). At the Fleur de Lys quarry, many of the preform scars left behind suggest success was achieved through trial and error. Broken preforms still clinging to the quarry illustrate the often weak, heterogeneous internal structure of soapstone. Heterogeneity within the rock structure, combined with the soft properties of talc and serpentine minerals, often make soapstone quarrying a risky endeavour. Therefore, removing chunks of soapstone from an outcrop requires skill, persistence and good luck. In addition, fresh unweathered soapstone was preferred at Fleur de Lys and at quarries in Wyoming (Frison 1982:275) where digging beneath the ground surface revealed the finest soapstone.

Quarrying toolkits recovered from the Westfield Steatite quarry in Westfield, Massachusetts also varied in their function, and local variations of quarrying tools indicate exploitation of regional, local raw materials. Fowler (1945:97-101) describes the functions of specialised tools such as rocker abraders, scraping chisels, shavers, scrapers, pipe reamers, drills, bits, end picks, corner picks, and hand gouges. This was also the case at other quarries in northeast United States and Canada where local materials were used in the construction of quarrying implements. According to Fowler (1947:148), at the Westfield Steatite quarry in Massachusetts, the target area was first outlined using a large pick-like implement (e.g., end pick or corner pick). Once the indentation was made to the carvers' specifications, the preform was undercut and extracted from the outcrop. Fowler (1947:148) suggests that, after slight modifications, the preform was then transported to another site, and the rest of the carving took place at another location. Hammerstones, scrapers and shavers were used in the final stages of vessel manufacture to ensure the desired form was achieved without breakage (Fowler 1947:152).

1.5 Provenance Studies of Soapstone

The goal of provenance studies is to determine the source of the raw material used to manufacture artifacts (Rapp 1985). In particular, the application of scientific techniques to archaeological materials has enabled archaeologists to pursue new directions in provenance studies. Semi-quantitative (e.g., petrography, XRD) and quantitative (e.g., trace element analyses) techniques are now used to correlate lithic quarries or outcrops with finished artifacts.

In previous provenance studies of soapstone, XRD, a technique in which minerals are identified based on their specific x-ray peaks, has been used as a preliminary step in sourcing soapstone. This technique, although a useful first step for determining the geological origin of soapstone, operates optimally in conjunction with other more sensitive trace element analyses. This is substantiated by a study by Robertson (1995) who analysed soapstone lamp fragments using XRD from a Dorset site on Little Cornwallis Island. The XRD data was inconclusive due to heterogeneous samples which indicated either the artifacts originated from one highly diverse source or many sources. The preliminary study serves to reinforce the difficulty of analysing such a heterogeneous rock type. However, it also shows that data from one semi-quantitative technique alone can be used as the basis for further studies. In another study, petrography and XRD analysis were first used to characterise the mineral assemblages of 375 talc and chlorite vessels from Southwest Asia, later followed by trace element analysis of the artifacts (Kohl et al. 1979). In spite of limited success in geologically "fingerprinting" the soft stone, it was apparent that the multi-technique approach has greater capacity for success than utilising one procedure only. For instance, a preliminary study of eleven soapstone vessels from a Dorset habitation site at Cape Ray, Newfoundland were compared with outcrop samples from the Fleur de Lys soapstone quarry (O'Driscoll 1998). The XRD data showed the Cape Ray Dorset likely did not obtain their soapstone from the Fleur de Lys quarry. Mineral concentrations from Cape Ray artifacts were consistent but did not match those from the quarry at Fleur de Lys, which exhibited significant intrasite variability. As a result, geochemical techniques are applied in this thesis to explore this provenance question more fully.

Quantitative whole rock major and trace element analyses can conceivably be used to identify and connect soapstone artifacts to their geological source. Major elements (>1% concentration) are used to assign soapstone samples to preliminary groups, while trace elements (concentrations of less than 1000 ppm or parts per million), particularly the REEs, provide information about the original chemical composition of the rocks and enable samples to be assigned a chemical fingerprint. This fingerprint can then be used to compared an artifact, or a set of artifacts, to one another and to potential outcrop sources.

Highly sensitive analytical procedures are needed to detect trace elements, which occur in low abundances. For instance, instrumental neutron activation analysis (INAA) is a technique that has been used to determine REE concentrations in soapstone. Allen and Pennell (1978), Allen et al. (1975), Luckenbach et al. (1975a), Nagle (1984), and Truncer et al. (1998), have applied INAA to soapstone artifacts. Allen and Pennell (1978:232) point out that although soapstone may exhibit variations in mineralogy, trace elements within the rock may not vary as much. Nagle (1984) employed INAA in an attempt to correlate Dorset soapstone cooking vessels from Newfoundland and Labrador with soapstone outcrops in coastal Labrador and northeastern Newfoundland. Nagle (1984) proposed a distance decay hypothesis which states that as one gets farther from an outcrop it is expected to see less of that raw material than if closer to the outcrop. This hypothesis could not be adequately tested, as the significant amount of soapstone along coastal Labrador and northeast Newfoundland complicated the study, making it difficult to trace artifacts to a particular source. In another study, INAA and radiochemical separation neutron activation analysis (RNAA) were used to determine REE concentrations of steatite (soapstone) from Shetland, samples that had minerals identified initially by XRD and XRF (Moffat and Buttler 1986:104). Heterogeneity of the steatite prevented Moffat and Buttler (1986) from making any definitive conclusions regarding artifact sources.

Problems with provenance studies of soapstone develop when detection limits are high, when sensitivity is low, and background noise prevents accurate and precise measurement. Furthermore, sampling procedures of mineralogically heterogeneous outcrops can pose problems for researchers. Soapstone is a very heterogeneous rock due to chemical alteration through physical and chemical processes. It has low concentrations of many trace elements, but the low instrument detection limits and the high sensitivity of ICP-MS, along with petrography, XRD and XRF, were used in this study to produce robust data.

1.6 Present Investigation: Sampling Procedure and Methodology

This thesis is based on field reconnaissance conducted during September 1999 and subsequent examination of the sampled material (Fig. 1.6). In total, forty-four outcrop and artifact samples were collected. Thirteen samples of soapstone-like rocks were collected from outcrops in western Newfoundland. Specimens were collected from Bear Cove Road (1), Fleur de Lys (5), St. Anthony (2), Straitsview (1), Tablelands (2), and along Trout River (2). These outcrops were chosen based on their similar mineralogy to the soapstone found at the Fleur de Lys quarry and the soapstone used by the Dorset to manufacture implements. Other sampling considerations included accessibility and proximity to Dorset sites.

Thirty-One artifact specimens for this research were obtained from collections at the Newfoundland Museum from Dorset sites at Cape Ray (6), Englee (8), Fleur de Lys (5), Pittman Site (5), and Port au Choix (7). Artifacts were selected based on a number of criteria including texture of the rock, quality of material, and degree of workmanship. Also complete artifacts were not chosen and samples were selected from sites where soapstone was recovered in abundance. Visual examinations of the artifacts were conducted to determine perceptible differences in mineralogy, texture and quality of

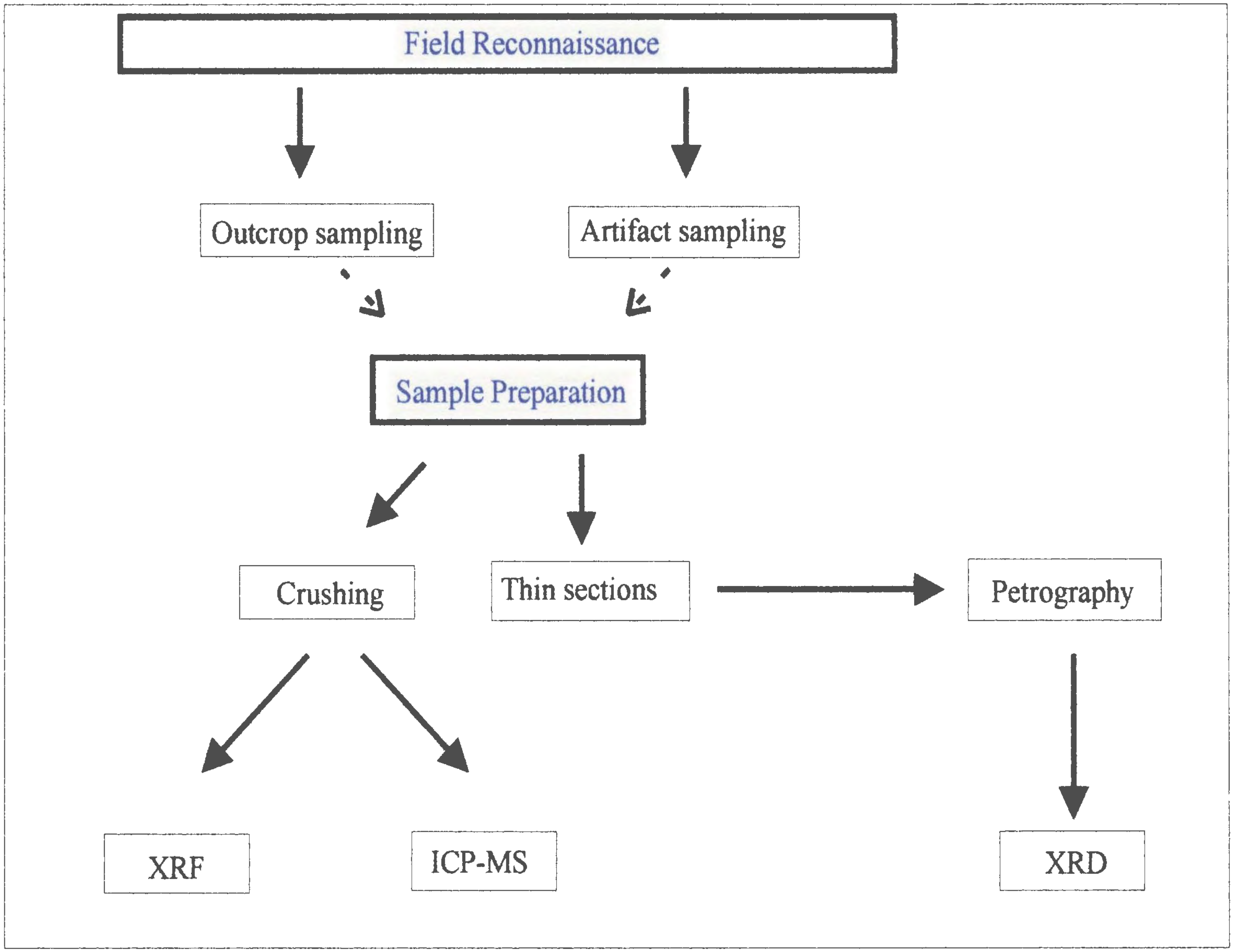


Figure 1.6: Schematic of Sampling Procedure and Methodology

material. For this research, reliable analyses were carried out on samples selected to provide accurate representation of the mineralogical variation at each site.

Petrographic examination of all forty-four thin sections was carried out to identify mineral assemblages and as a preliminary step in grouping samples. XRD was used on fourteen samples to identify minerals not clearly defined through petrographic analysis. XRF was conducted on all samples to determine bulk rock chemistry (major and minor element abundances). As trace element and REE concentrations were typically below the detection limits of XRF, they were determined by ICP-MS. These tests were conducted in the XRD laboratory, XRF laboratory and ICP-MS laboratory respectively, at Memorial University.

CHAPTER TWO

DESCRIPTION OF DORSET SITES AND ARTIFACT ASSEMBLAGES FROM WEST NEWFOUNDLAND

2.1 Introduction

Thirty one artifacts were obtained from collections at the Newfoundland Museum from five Dorset sites: Cape Ray (6), Englee (8), Fleur de Lys (5), Pittman Site (5), and Port au Choix (7). Soapstone artifacts are well represented at these sites, and it was possible to obtain a sample of the mineralogical variation within the sites through visual examinations of the artifacts to determine perceptible differences in mineralogy, texture and quality of material. A description of the five Dorset sites under investigation and the results of the petrography and x-ray diffraction (XRD) analyses of the artifacts are discussed in this chapter.

2.2 Classification and Mineralogy of Ultramafic Rocks

Igneous rocks may be classified according to their modal mineral content, as outlined by the International Union of Geological Sciences (IUGS) (e.g., Le Maitre 1989; Appendix Four). Classification and nomenclature of ultramafic rocks are based on there being more than 90% mafic minerals (olivine, orthopyroxene, clinopyroxene, pyroxene, hornblende) and the proportions of these mafic minerals to one another (LeMaitre 1989:21). These constitute the primary mineral assemblages of rocks that have not been altered. Soapstones are altered ultramafic rocks that are most likely derived from peridotite or dunite parent (Bucher and Frey 1994:159-168).

The rocks examined in this study are comprised mainly of secondary mineral assemblages. The primary mineral assemblages have been changed as a result of alteration processes such as metamorphism, serpentinisation, and carbonatisation (explained in detail in Chapter Three). During these alteration events, new minerals are formed at the expense of the primary minerals (Fig.2.1). These secondary minerals include talc, serpentine, and carbonates (i.e., magnesite).

2.3 Site and Artifact Descriptions

In order to classify the soapstone assemblages at each of the Dorset sites sampled, it is necessary to describe and differentiate artifacts based on mineralogy. This is achieved through petrography and XRD analysis. Specific modal mineral abundances and the XRD scans and peak listings are presented in Appendix One.

2.3.1 Cape Ray

Located in southwestern Newfoundland, the Dorset site at Cape Ray consists of a large habitation site with a smaller Groswater component. The topography, coastal location and wide array of seasonally abundant resources at Cape Ray make it a prime locale for Dorset habitation. During the spring and early summer months, harp seals (*Phoca groenlandica*), capelin (*Mallotus villotus*), codfish (*Gadus morhua*), salmon (*Oncorhynchus* sp.), and birds are readily obtained within close proximity of the site and small mammals such as red fox (*Vulpes vulpes*), Arctic hare (*Lepus arcticus*), and beaver

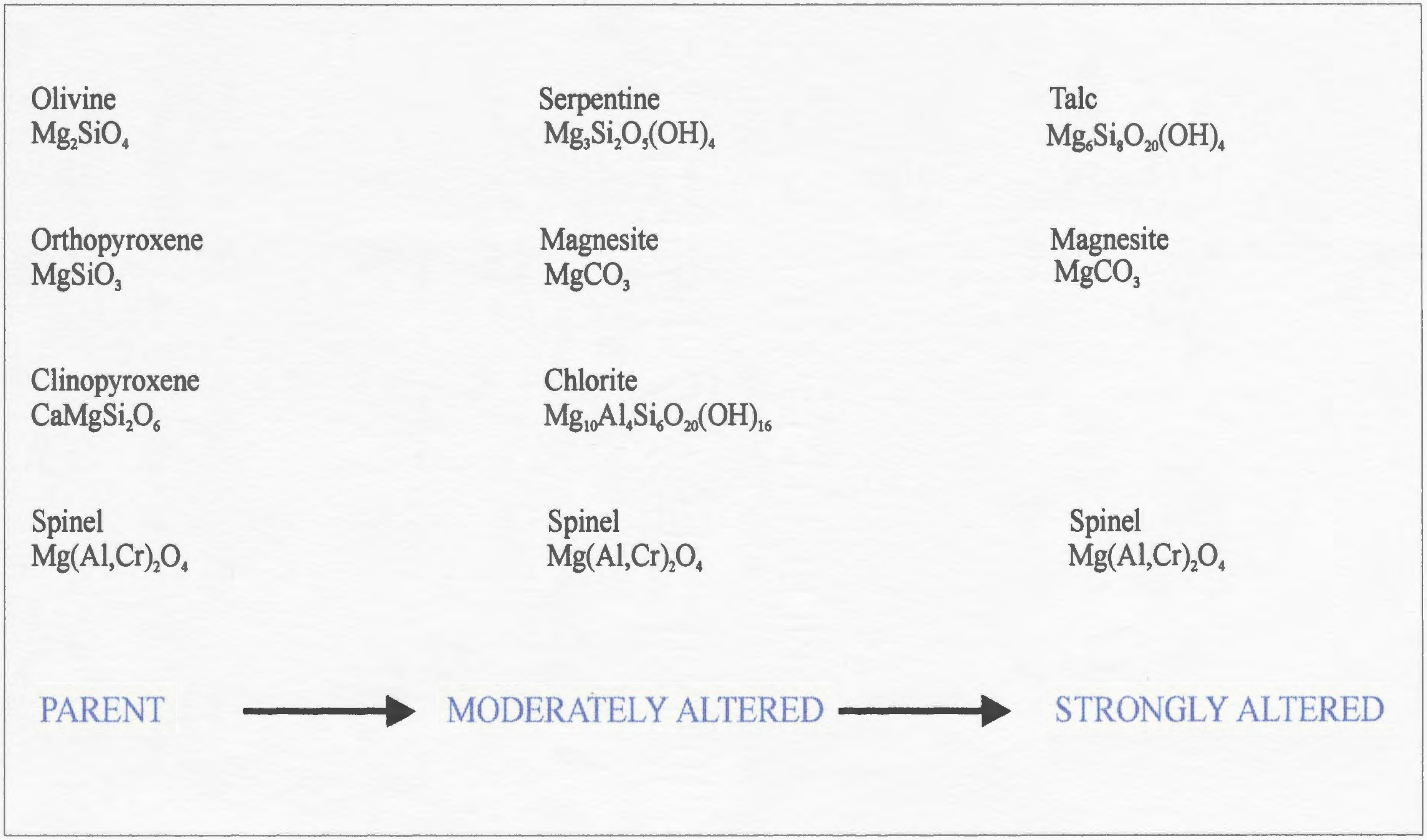


Figure 2.1: Mineralogy of Parent and Altered Samples

(*Castor canadensis*) would have supplemented the mainly marine diet of the Dorset. Plant resources, including berries, are abundant in the area and were probably enjoyed by prehistoric cultures.

Helen Devereaux first surveyed Cape Ray in 1965 in search of undisturbed archaeological sites (Devereux 1966). The evidence she found, coupled with the threat of human disturbance, prompted further investigations by Urve Linnamae two years later. Through Linnamae's excavations in 1967 and 1968, seven areas (Areas A to G) of high archaeological potential were designated, and of these, Areas C, E, and F were classified as the main occupation areas (Linnamae 1975:29). An abundance of lithic artifacts were recovered from Linnamae's excavations, including the typical Dorset tool kit composed of microblades, triangular endblades, endscrapers, burin-like tools, ground slate implements, and soapstone (Linnamae 1975:101). The soapstone assemblage consisted of 672 cooking vessel and lamp fragments (Linnamae 1975:150). Organic items were rare as acidic soil conditions prevented most organic preservation.

Lisa Fogt resumed excavations at Cape Ray in 1996. Fogt's investigations concentrated on Area C in 1996 and Area E in 1997; two of Linnamae's high potential areas. In 1996, Fogt investigated the lack of evidence for a dwelling in Area C, an area that presumably had extensive Dorset occupation (Fogt 1998). A Dorset dwelling was uncovered in Area C as well as over 2,300 artifacts, including microblades, endblades, retouched flakes, endscrapers, soapstone vessel fragments, core fragments, tip flute spalls, ground slate, bifaces, and utilised flakes (Fogt 1998). In 1997, Fogt's excavations revealed evidence for structural remains in Area E. Area E turned out to be a multifunctional activity area comprised of a large external hearth feature, a midden, and some hold-down rocks that indicate the remains of a dwelling. Virtually the same types of artifacts were recovered from the 1996 and 1997 excavations, although soapstone fragments were less represented in the 1997 assemblage (Fogt 1998, pers.comm.).

2.3.1.1 Petrographic Observations

Most of the artifacts from Cape Ray are constructed from medium to fine grained soapstone (Fig.2.2) and were manufactured by gouging and grinding to approximately 1 inch thick. This gives the soapstone a smoother appearance than is typical. Many artifact fragments are stained on both sides with a black residue, which is generally thought to be residues from the cooking of seal. However, a residue analysis of two soapstone vessels, one from Philip's Garden and one from Point Riche, Newfoundland (Deal 1990:10) suggests that freshwater fish may also have been cooked in soapstone vessels. Small talc crystals are visible in some hand samples due to their iridescence and flat, scaly habit.

In thin section, the samples from Cape Ray are fine grained and dominated by talc (40-50%), chlorite (30-40%), serpentine (<10%), magnesite (10-15%), and spinel (5-15%) (Fig.2.3). Talc occurs as fine grained aggregates forming irregular, subhedral boundaries with chlorite, serpentine and magnesite. Individual mineral grains of talc are indistinguishable, as are serpentine grains, which are in massive groups. The average size of a single magnesite grain is 1 mm. An iron oxide weathering rind is mostly evident at the margins of magnesite and quartz grains.

Compared to soapstone artifacts from other Dorset sites in western Newfoundland,

Figure 2.2: Cape Ray Artifact CjBt-1: 3121

Mineral annotations are used following Kretz (1983):
Mgs = Magnesite, Srp = serpentine, Spl = Spinel, Tlc = Talc.

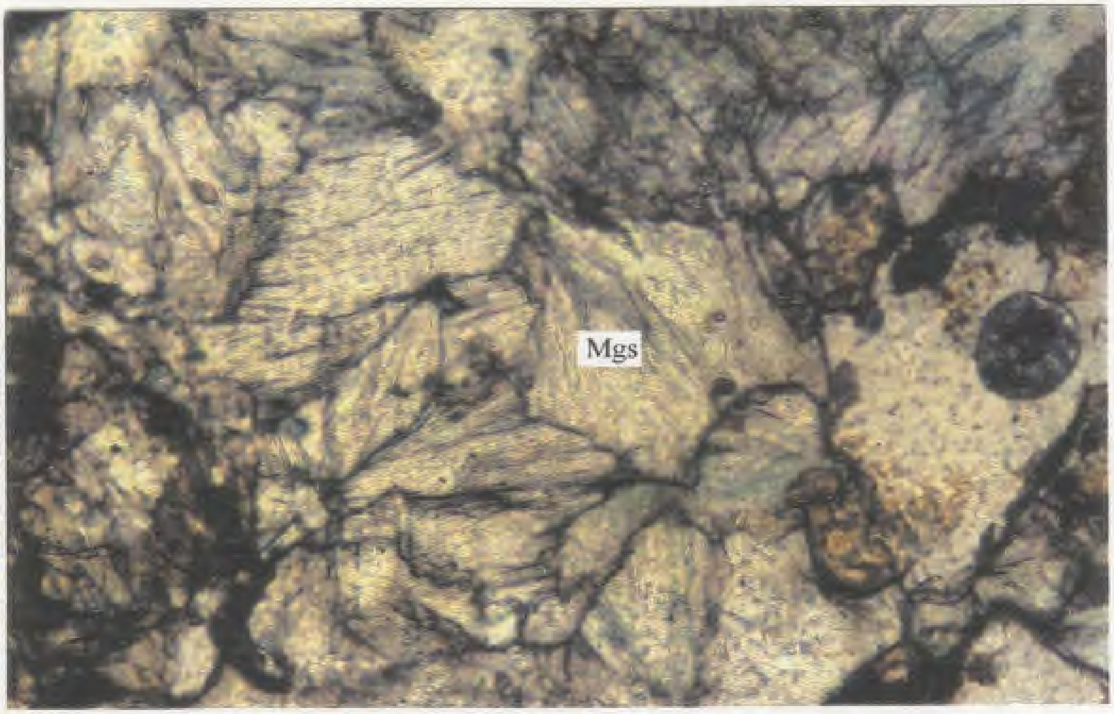


Figure 2.3: Photomicrograph of artifact CjBt-1:2896 from the Cape Ray site. In plane polarised light (ppl) and at 10x magnification.

soapstone from Cape Ray has higher amounts of chlorite (clinochlore) and lesser amounts of magnesite, which indicates the lack of a significant carbonate phase. Spinel comprises 5% to 10% of the rock composition but provides a link from the highly altered soapstone back to the original protolith. In general, the rocks from Cape Ray have been serpentinised but not significantly carbonated.

The XRD analysis corroborates the petrography and shows that talc, clinochlore and magnesite are the main minerals in the rock assemblage (Appendix One). This is the case for all samples tested from Cape Ray and is consistent with the thin section interpretation.

2.3.2 Englee

In the community of Englee, located on the east coast of Newfoundland's Great Northern Peninsula, three significant Dorset sites (EeBa-1, EeBa-2, EeBa-3) were excavated in 1969 and 1972 by James Tuck. The Lane's Cove (or Englee) burial site (EeBa-1) was located in one of two limestone caves near the mouth of Englee Harbour. Twenty-one artifacts were recovered from this site in addition to some skeletal material comprised of the almost complete remains of an eight-year-old child and associated burial goods (Anderson and Tuck 1974). The Lane's Cove site (EeBa-2) appears to be the richest Dorset site at Englee in terms of lithic artifacts recovered. A radiocarbon date for EeBa-2 suggests Dorset occupation at 1585 +/- 95 BP (I-4379) (Anderson and Tuck 1974; Wilmeth 1978:194). Hundreds of Dorset artifacts including end scrapers, soapstone vessel fragments, and triangular endblades were discovered (Anderson and Tuck 1974:91).

In contrast, only twelve artifacts were recovered from EeBa-3, also known as the Englee site, however substantial faunal material was recovered from this site and was later analysed by Raymond LeBlanc (1975).

2.3.2.1 Petrographic Observations

In hand sample, the soapstone from Englee is noticeably different from soapstone from Cape Ray and Port au Choix. The texture of the soapstone is different, it is porous and more granular (Fig.2.4). Iridescent talc grains are often visible in hand sample.

The artifacts from Englee range from medium to fine grained and are dominated by talc (35-50%), magnesite (40-45%), serpentine (5-15%), and spinel (5-10%). One exception is sample E682 which has minor talc (5-10%), and XRD analysis shows significant amounts of quartz, albite (feldspar), and spinel. This rock cannot be easily carved due to the significant amount of quartz present and is probably not an artifact.

Artifacts from this site are often equigranular with some larger talc grains measuring 1 to 2 mm. Talc occurs as fibrous aggregates/masses and grains are subhedral to anhedral. Single talc crystals are difficult to distinguish with seemingly no preferred orientation. Boundaries between talc and magnesite and talc and serpentine are irregular.

Magnesite grains are anhedral, rhombehedral (sometimes elongated) and occur in clustered groups. Individual magnesite grains range in size from 1 to 4 mm, and grain boundaries are rounded.

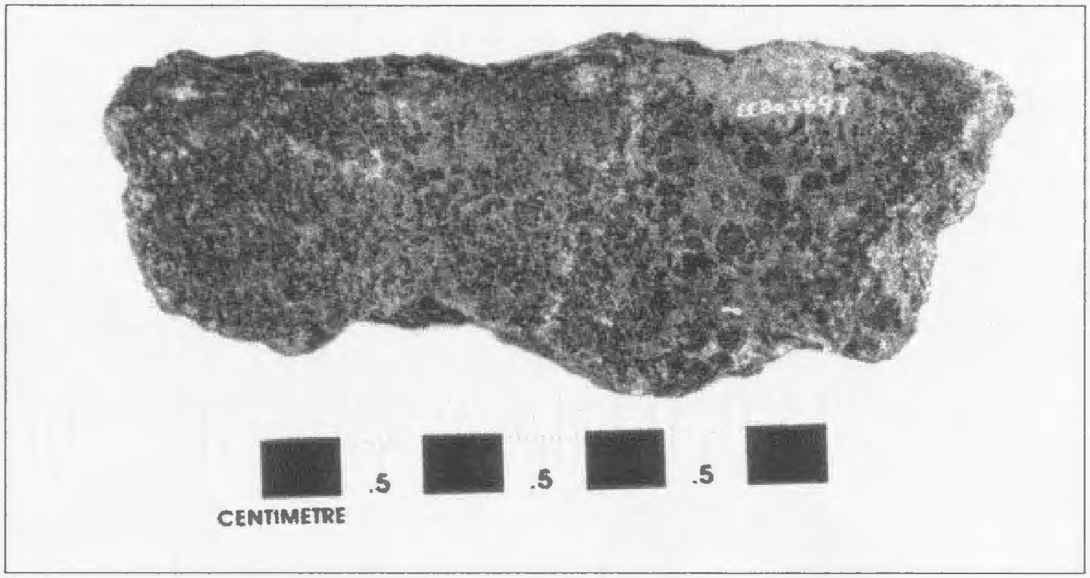


Figure 2.4: Englee artifact EeBa-1: 697

2.3.3 Fleur de Lys

Within the community of Fleur de Lys, on Newfoundland's Baie Verte Peninsula, is the only known soapstone quarry site on the island. Exploitation of the quarry was conducted by the Dorset between 2,000 and 1,200 B.P. The quarry is comprised of five different "Localities" throughout the town of Fleur de Lys with Localities 1 to 3 comprising the main quarried outcrops (Fig.2.5). Locality 1 is the main quarry face and is divided into Groups A to F. Locality 1 consists of a long bedrock cliff of extensively quarried soapstone extending about 200m north-east (Nagle 1982:106). Locality 2 is located approximately 200m east of Locality 1 and Locality 3 is along the water in Fleur de Lys Harbour. Soapstone was quarried at this site and the presence of finishing implements indicates that at least some vessels were fully manufactured at the quarry.

Initial investigations of the soapstone quarry at Fleur de Lys were by Howley (1980), Jenness (1972), Linnamae (1975), and Wintemberg (1940). However, archaeological fieldwork did not commence at this site until 1981 when Christopher Nagle began testing and excavating the most extensively worked areas, that is Groups A, B and C at Locality 1 (Nagle 1982). Through test excavations, Nagle (1982:102-103) hoped to ascertain the quarry's cultural affiliation and to learn as much as possible about the quarrying process. A Dorset presence at Fleur de Lys was not established during the first field season, but Dorset utilisation of the quarry was assumed (Nagle 1982:105). This was based in part on the size and shape of the extracted preforms on the main quarry face, which are rectangular and characteristic of Dorset vessel forms. The importance of this site

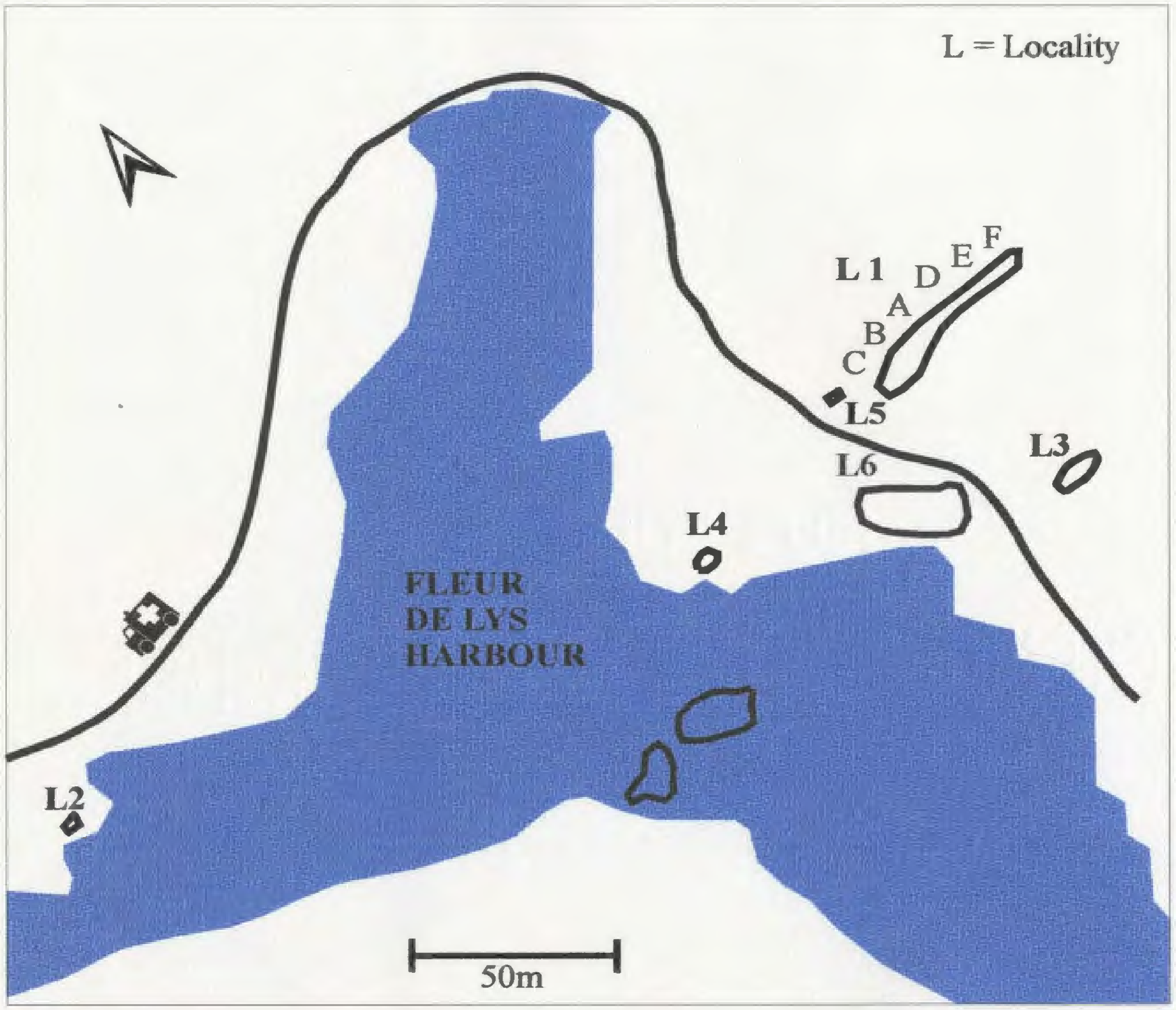


Figure 2.5: Schematic of the Fleur de Lys Quarry Localities 1-6 (adapted from Thomson 1989:250).

as a source of data for soapstone quarrying techniques by prehistoric groups was realised immediately and effort was placed into further developing this site (Thomson 1983,1984,1985).

Subsequent investigations have proven increasingly successful. Most recent excavations in 1997 and 1998 have helped us to further understand the prehistory of Fleur de Lys. In particular, a Dorset connection to the quarry was fully established in 1997 through the recovery of diagnostic Dorset hunting implements (Erwin 2000). These consisted of three endblades and a quartz crystal microblade associated with the Dorset component of the site.

2.3.3.1 Petrographic Observations

In hand sample, soapstone from Fleur de Lys has holes in the surface which are a result of the dissolution of carbonate minerals during the weathering process, and this is similar to soapstone from the Pittman site and Englee (Figs.2.4; 2.6; 2.7). The artifacts are dominated by talc-carbonate phases including talc (40-50%), magnesite (25-45%), and serpentine (5-20%), along with accessory spinel (5-10%) (Figs.2.8; 2.9). Individual talc crystals are indistinguishable and occur in aggregates. Magnesite grains are between 1 and 2 mm in size. Minor fine grained serpentine and opaque spinel complete the assemblage.

2.3.4 Pittman site

The Pittman site (DkBe-1) is located on Sop's Island in western White Bay. The site has two cultural components, Maritime Archaic and Dorset (Linnamae 1975:51). The

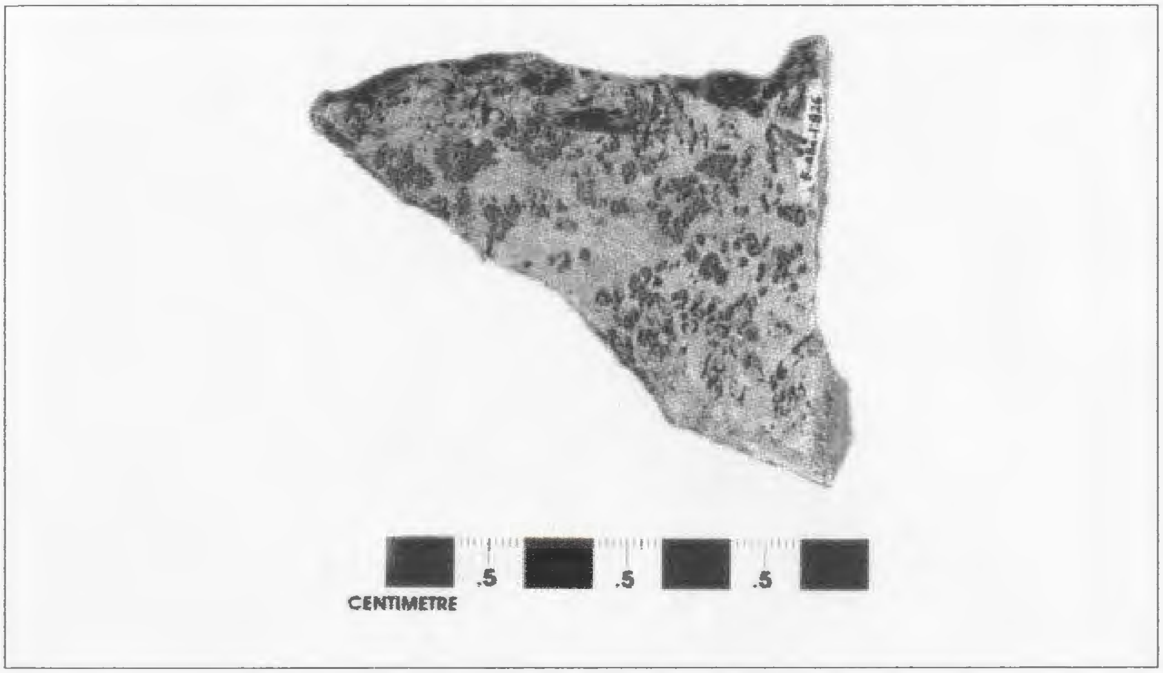


Figure 2.6: Fleur de Lys Artifact EaBa-1: 826

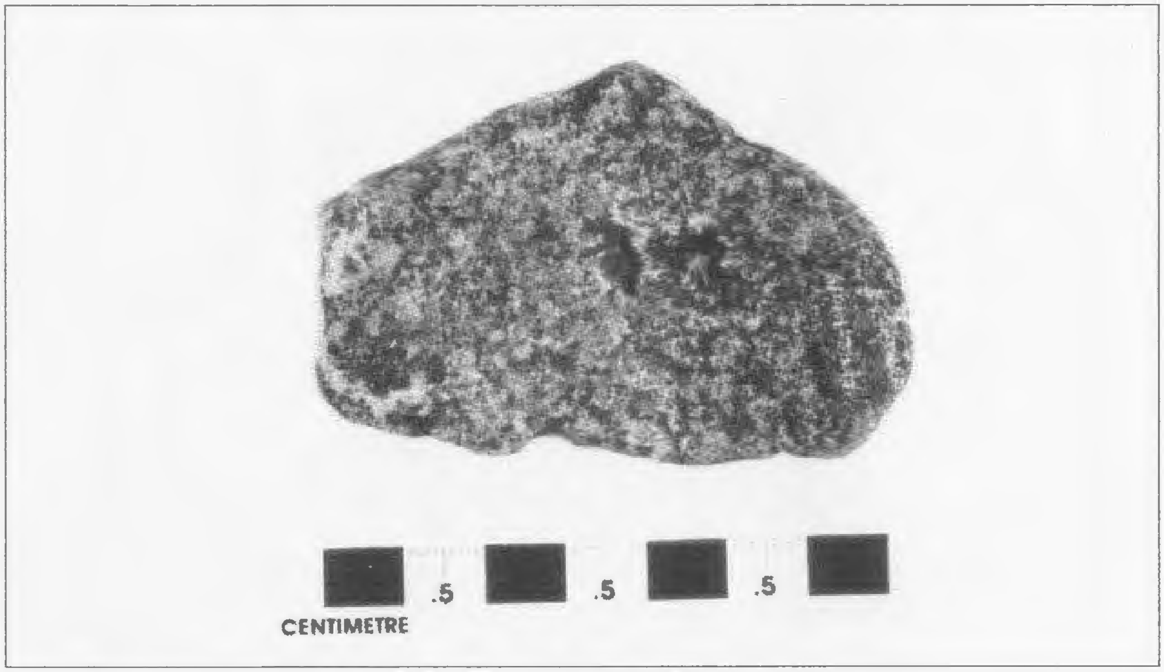


Figure 2.7: Pittman site artifact DkBe-1: 1019

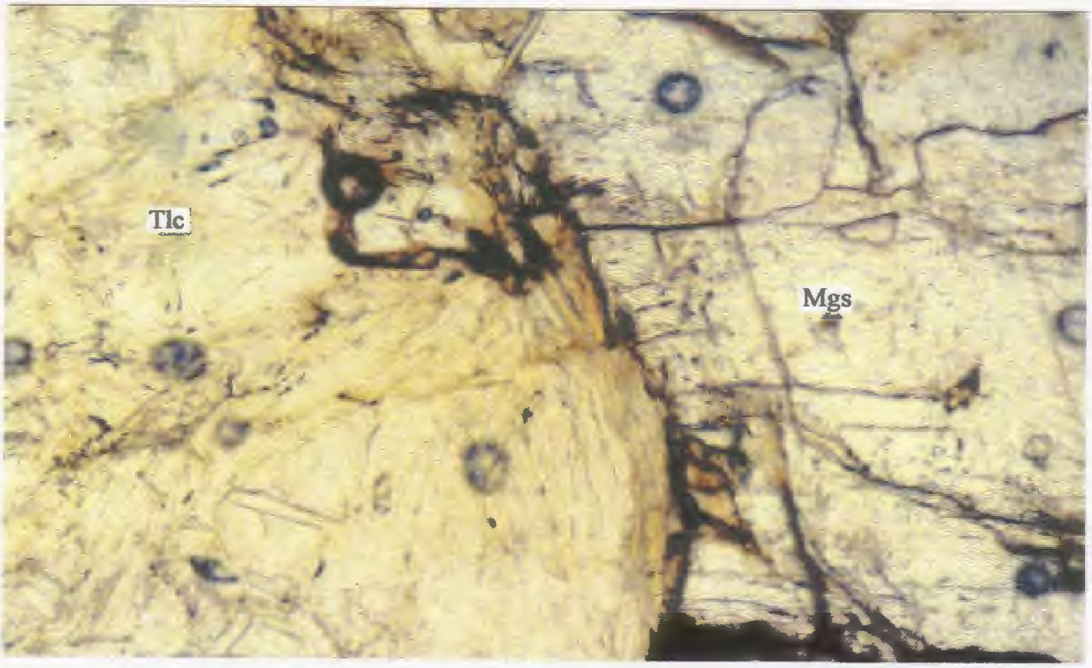


Figure 2.8: Artifact EaBa-1: 826 from Fleur de Lys. Field of view = 1.5mm, ppl, 10x magnification.

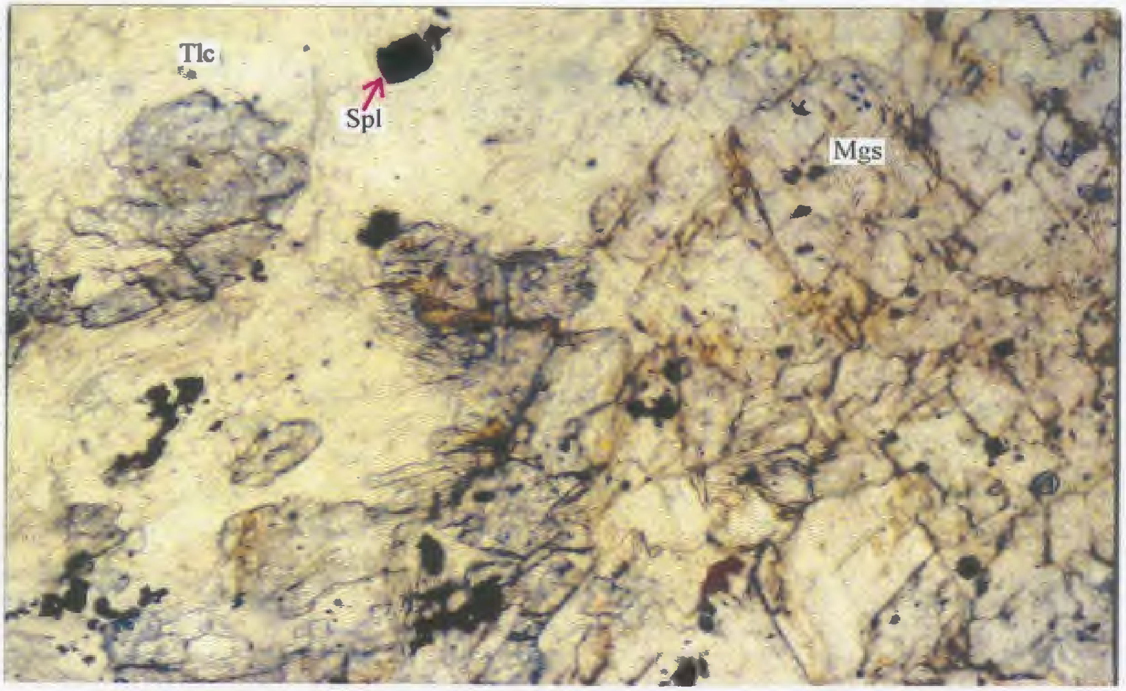


Figure 2.9: Artifact EaBa-1: 1661 from Fleur de Lys. Field of view = 1.5mm, ppl, 10x magnification

area has good terrestrial, marine and freshwater resources including access to caribou (*Rangifer tarandus*), seal and salmon. Exploitation of these resources indicates the Sop's Arm area was likely inhabited by prehistoric cultural groups from March until October (Linnamae 1975:54).

This site has been visited by many archaeologists since T.G.B. Lloyd explored the area in 1873 (Lloyd 1875b). The first major excavations began at the site in 1967 under the direction of Urve Linnamae (Linnamae 1975). Both Maritime Archaic and Dorset artifacts were recovered from preliminary test pits and excavations at the site, though Dorset occupation was more extensive (Linnamae 1975:50-51).

Fifty-five soapstone fragments were recovered from the Pittman site (Linnamae 1975:204). It is expected that, based on the close proximity of the Pittman site to the Fleur de Lys quarry, the mineralogy and geochemical analyses of the Pittman site soapstone analysis will indicate that the soapstone originated at Fleur de Lys. Linnamae (1975:208) suggests Fleur de Lys may be the possible quarry source from which the Pittman site soapstone originated and bases this claim on visual characteristics.

2.3.4.1 Petrographic Observations

Linnamae (1975:208) pointed out that soapstone from the Pittman site resembled soapstone from the quarry at Fleur de Lys in texture and grain size (e.g., Figs.2.4; 2.5). This is evidenced by the dominant talc-carbonate assemblages and accessory spinel, serpentine, and quartz. The fresh surfaces of the rocks are blue, and a rust-coloured iron oxide weathering rind envelops them.

In thin section, the artifacts are dominated by talc (40-60%), magnesite (30-40%), serpentine (15-20%), quartz (5%), and spinel (5%) (Figs.2.10; 2.11). The talc matrix is comprised of bladed, massive bundles bordering magnesite. Single talc crystals are indistinguishable. Magnesite grains are typically 1 mm in size and occur in subhedral lobes.

2.3.5 Phillip's Garden, Port au Choix

The largest and most prolific Palaeoeskimo site on the island is located in Port au Choix on the Great Northern Peninsula. Both the Groswater and the Dorset are represented at Port au Choix at twenty known sites dating from 2800 to 1300 B.P., but four of these sites represent the main occupation areas (Renouf 1994). One Dorset site, named Phillip's Garden (EeBi-1), was initially reported by W.J. Wintemberg (1939, 1940) and partially excavated by Elmer Harp Jr. between 1961 and 1964 (Harp 1964). It was a substantial beachfront site, occupied throughout the spring, summer and winter months and was a very successful sealing site (Renouf 1994). During the 1980s and into the 1990s, M.A.P. Renouf conducted excavations at Phillip's Garden. Over fifty house depressions have been identified at the site, with both winter and summer dwellings represented (Renouf 1994:198-201). Early occupation of the site was moderate but increased until occupation peaked by 1350 B.P., and then diminished steadily until 1250 B.P. when the last evidence for Dorset occupation at the site (Erwin 1995). Lithic materials recovered from the site include the typical Dorset toolkit of chert endblades, quartz crystal microblades, and fragments of soapstone vessels.

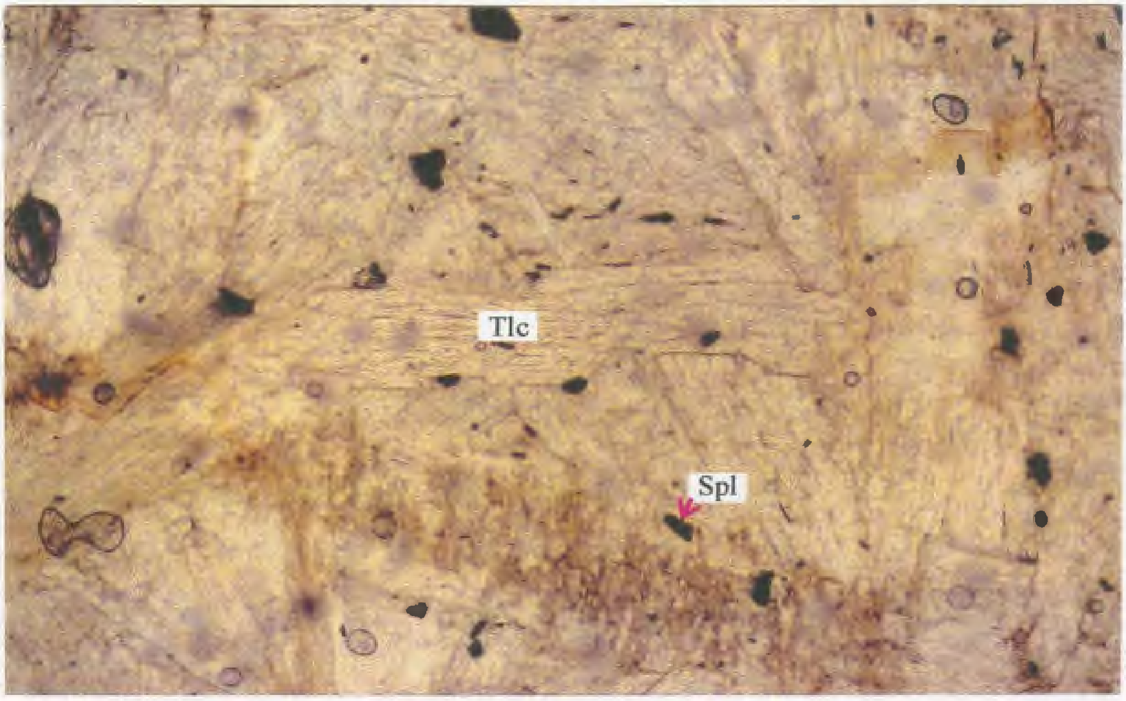


Figure 2.10: Artifact DkBe-1:1019 from the Pittman site. Field of view is 1.5mm, ppl, 10x magnification.

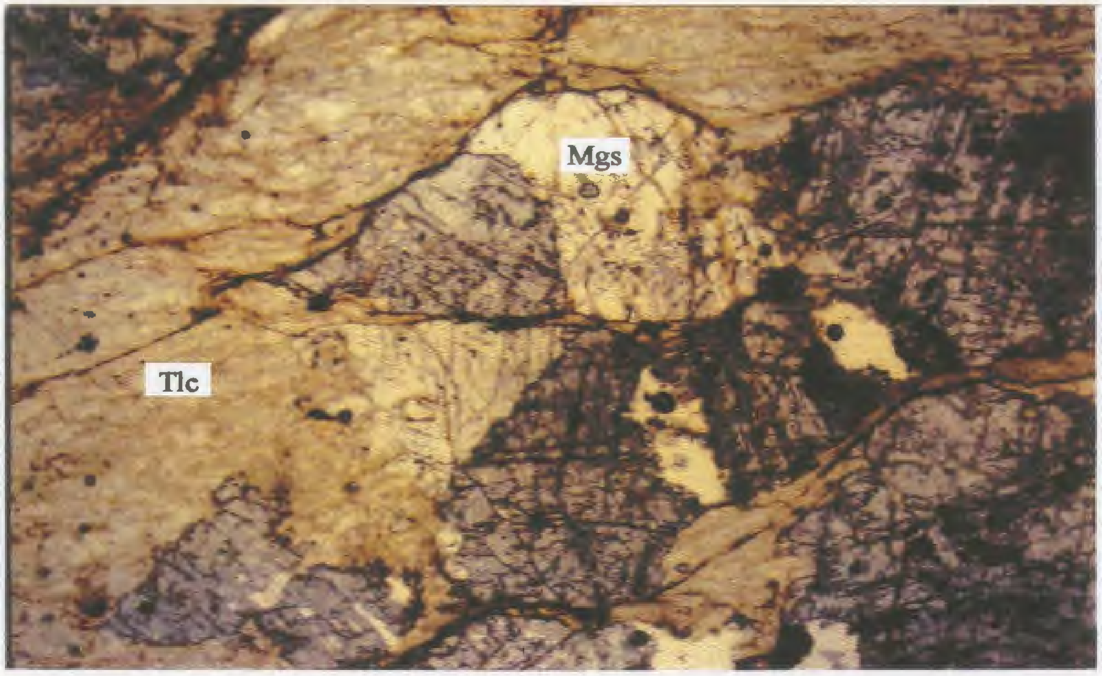


Figure 2.11: Artifact DkBe-1: 1020 from the Pittman site. Field of view is 8mm, ppl, 2.5x magnification.

2.3.5.1 Petrographic Observations

Soapstone from Port au Choix is fine grained in hand sample and is similar to soapstone from Cape Ray with regard to porosity (i.e., small pores), grain size and texture (Fig.2.12). In thin section, the Port au Choix artifacts contain mainly talc (40-60%), chlorite (25-35%), magnesite (15-20%), and spinel (5%) (Fig.2.13). Talc is in fibrous aggregates and single crystals are indistinguishable. Magnesite occurs as subhedral lobes and is sometimes rhombehedral-shaped. An iron oxide weathering rind surrounds magnesite grains at margins.

Three artifacts from Port au Choix (EeBi-1:19040; EeBi-1:3952; EeBi-1:14128) exhibit unique mineralogy; the grains are much the same size throughout and are interlobular with equal parts of talc and chlorite and minor magnesite and spinel. Chlorite (i.e., clinochlore) grains are smaller than in other, similar soapstone samples, occurring in massive, tight-knit bundles.

2.4 Summary of Chapter Two

The Dorset are evidenced in the archaeological record by a stone and bone technology reflective of their maritime resource strategy. Soapstone cooking vessels and lamps are one component of an extensive stone tool technology which is characterised by microblades, endblades, scrapers, and burin-like tools. The soapstone artifacts sampled here are from prolific Dorset sites in western Newfoundland; Cape Ray, Englee, Fleur de Lys, Pittman site, and Port au Choix (Phillip's Garden). The artifacts' fresh surfaces are dark blue-green and a rust-coloured weathering patina conceals the rocks' interior.

Figure 2.12: Port au Choix artifact EeBi-1: 4833

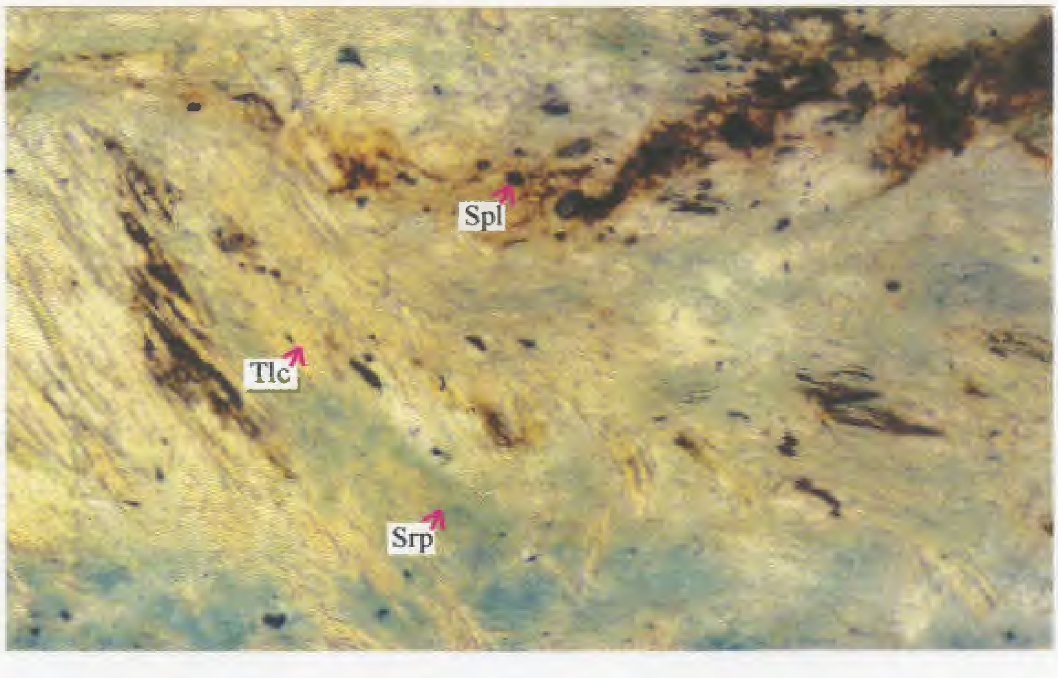


Figure 2.13: Photomicrograph of artifact EeBi-1: 14128 from Port au Choix. Ppl, 10x magnification.

The main petrographic features include:

- Talc-carbonate mineral assemblages with lesser amounts of minerals such as serpentine, spinel, and quartz.
- Talc occurs mainly as a matrix of anhedral fibrous aggregates where single crystals are rarely distinguishable.
- Magnesite grains are often rhombehedral-shaped, lobate and in groups of smaller subhedral grains or one larger grain.
- Serpentine (mainly antigorite) is extremely fine grained and occurs mostly as fibres intermixed with talc.
- Chlorite (clinochlore) is predominant in samples from Cape Ray and Port au Choix, and is not seen in other artifact thin sections and XRD.
- Spinel is the only remaining mineral from the original rock composition and comprises 5-10% of the mode in some of the artifacts.
- Where quartz is present it occurs in less than 10% of the rocks. The amount of quartz depends entirely on the amount of alteration. More altered rocks contain quartz as quartz is the final alteration product of the talc-magnesite chemical reaction series in metamorphic rocks.

Linnamae (1975:208) first suggested the possibility that soapstone from the Pittman site was mined at the Fleur de Lys quarry but that soapstone from Cape Ray site probably originated elsewhere. Linnamae's observations are based on the porosity of the soapstone from Fleur de Lys and the Pittman site, as well as the close proximity of the Pittman site to the Fleur de Lys quarry. The petrographic analysis employed here supports Linnamae's hypothesis. The mineralogical features of these artifacts indicate that the soapstone from the Pittman and Englee sites may have originated at the Fleur de Lys quarry, while the Port au Choix and Cape Ray soapstone likely originated at as-yet unidentified quarries (possibly along the west coast). The geochemical data presented in Chapter Four will further explore these ideas of provenance.

CHAPTER THREE

DESCRIPTIONS OF ULTRAMAFIC GEOLOGICAL ROCK UNITS FROM WEST NEWFOUNDLAND

3.1 Introduction

Thirteen samples of serpentinised ultramafic rocks were collected from western Newfoundland. Specimens were collected from outcrops on Bear Cove Road on the Baie Verte Peninsula (1), Fleur de Lys (5), Tablelands along Trout River Pond in Gros Morne National Park (2), along Howe Harbour near St. Anthony (2), and Straitsview (Spillar's Cove) (1) (Fig.3.1). These outcrops were chosen based on their mineralogical composition, that is, similarity in overall composition to the soapstone found at the Fleur de Lys quarry and the soapstone used by the Dorset to manufacture implements. The following is a review of the geology of west Newfoundland and unit descriptions of the geological outcrops sampled. Corresponding petrographic and XRD data will also be presented in this chapter.

3.2 General Framework

The Earth's mantle is composed primarily of magnesium-rich ultramafic rocks, with the general rock name peridotite (Bucher and Frey 1994:15). These mantle rocks are emplaced into the Earth's crust by dynamic tectonic processes during orogenesis, or mountain-building events. Mantle rocks exist in the Earth's crust in two forms: (1) mantle fragments from beneath oceanic crust and (2) mantle fragments associated with continental crust (e.g., harzburgite, dunite) (Bucher and Frey 1994:147). Mantle rocks from beneath continental crust include: (1) peridotites in fluid-deficient areas or; (2)

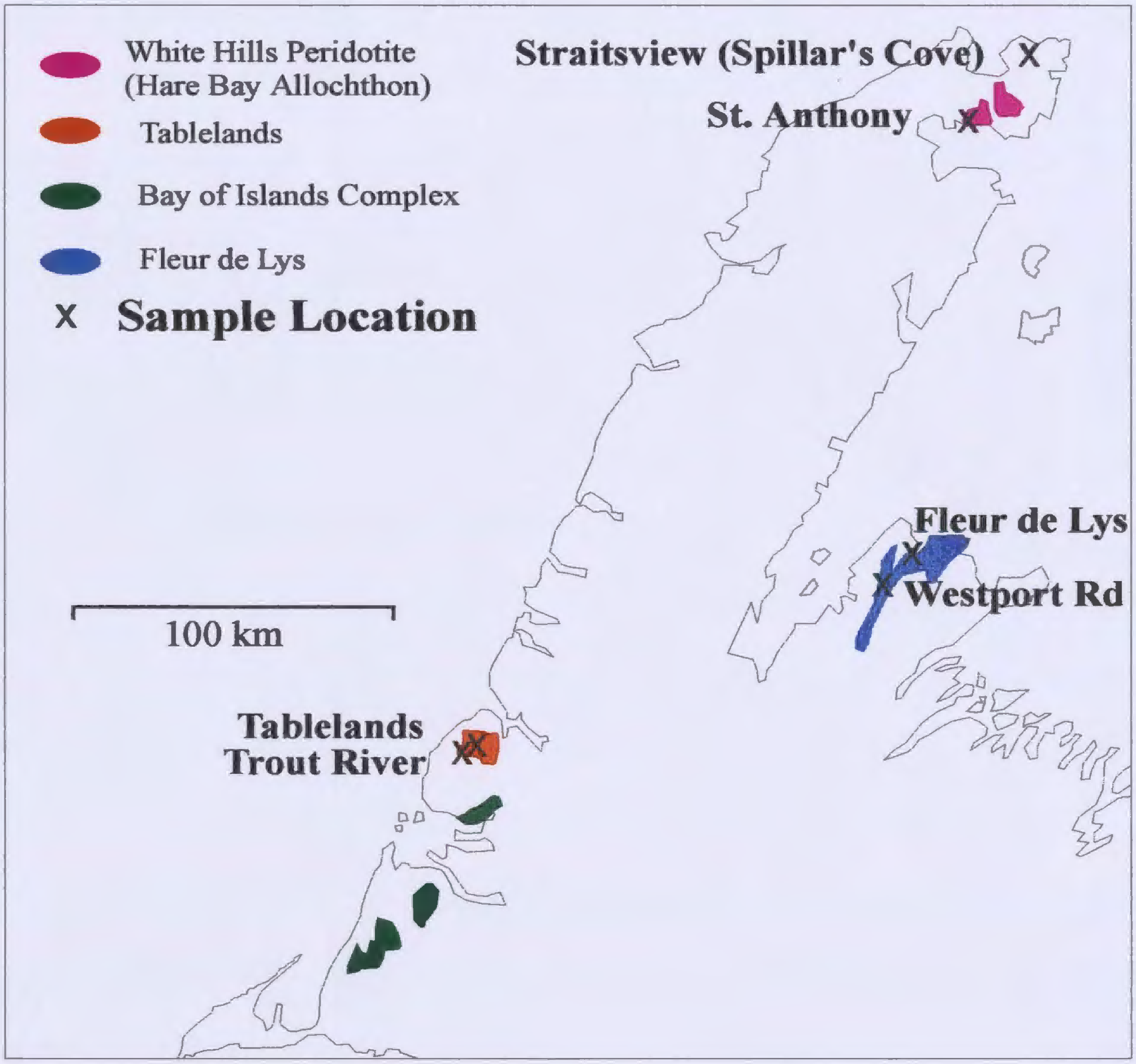


Figure 3.1: Schematic of outcrop sampling areas for this study

serpentinite, talc-shists where reactions with fluid have changed the mineralogy (Bucher and Frey 1994:159). Most ultramafic rocks contain minerals with a high water content such as amphibole and sheet silicate minerals (i.e., minerals with a planar structure that break off in sheets) such as talc, chlorite, and carbonate minerals. Other minerals commonly found in ultramafic rocks include forsterite, enstatite, lizardite, antigorite, brucite, dolomite, calcite, quartz, tremolite, diopside, and chrysotile (Bucher and Frey 1994:149-150).

3.2 Chemical and Physical Processes

Most ultramafic rocks in ophiolite sequences have been significantly altered, both physically and chemically, through metamorphism, serpentinisation, and carbonatisation, which are secondary alteration processes that occur under certain fluid-rich conditions. These processes result in the formation of the talc and serpentine, as well as carbonate and other minerals characteristic of soapstone.

3.2.1 Metamorphism, Serpentinisation, and Carbonatisation

Metamorphism results in changes in the mineralogy and/or physical structure or chemical composition of a rock. Tectonic (mountain-building) events that involve continental and oceanic plate movements/collisions often provide the impetus for metamorphism (Bucher and Frey 1994:13). Alterations in rock physical structure and/or chemical composition through metamorphism are not related to surficial activities such as weathering and erosion, but are controlled by pressure and temperature conditions (Bucher and Frey 1994:3). Temperatures may range from 150 +/- 50 degrees Celsius (low-grade metamorphism) to 650-1100 degrees Celsius (high-grade metamorphism) and pressure conditions may reach 15-20 kbar (Bucher and Frey 1994:3-5). Volatile elements such as H_2O and CO_2 are stored in minerals such as mica, amphibole and carbonate, and are released during these pressure and temperature fluctuations (Bucher and Frey 1994:14). The chemical composition and structure of the protolith largely control the chemical composition of metamorphic rocks and specific minerals are formed through differential temperature and pressure conditions. Due to chemical reactions within the rock through metamorphism, the original mineralogy of the protolith is often changed and new minerals are formed at the expense of old, primary minerals (Bucher and Frey 1994:45). Metamorphic rocks include peridotite, serpentinite, and soapstone.

Altered low-grade metamorphic rocks, which have originated from normally carbonate-free ultramafic rocks, are formed through the addition of H_20 and CO_2 from an external source through the processes of serpentinisation and carbonatisation (Bucher and Frey 1994:164-166). Serpentinisation can occur in three different environments: 1) in the Earth's mantle; 2) in oceanic ophiolite complexes and associated with oceanic metamorphism; 3) in the crust during collision belt formation (Bucher and Frey 1994:159). It is controlled by the amount of fluids pumped through the rock along fractures, shear zones and grain boundaries and results in the formation of serpentine from an olivine-pyroxene-bearing peridotite protolith (O'Hanley 1991:21). The passage of CO_2-rich fluids through the rock is known as carbonatisation. This causes reactions with the minerals present to precipitate a mineral such as magnesite ($MgCO_3$).

3.3 Outcrop Study Areas and the Geology of Western Newfoundland

The outcrop study areas for this research were chosen based on information accumulated from geological mapping of western Newfoundland and their proximity to Dorset sites. Due to the heterogeneity of peridotite-derived rocks (e.g., soapstone) there can be significant mineralogical variation within and between outcrops. Emphasis was placed here on obtaining representative samples of each outcrop and sampling rocks that display the range of alteration present in certain outcrops. This was achieved by examining each outcrop and sampling those areas that are seen as representative of that individual rock unit.

Western Newfoundland is made up of both transported (allochthonous) and locally derived (autochthonous) rocks. The Precambrian (Appendix Three) basement rocks of western Newfoundland are covered by autochthonous Palaeozoic sedimentary rocks which in turn are overlain by allochthonous Palaeozoic sedimentary and igneous rocks (Malpas 1976:20). The allochthonous sequence consists of the Humber Arm Allochthon (Bay of Islands area) and the Hare Bay Allochthon at the northern part of the Great Northern Peninsula. These allochthonous rocks are further divided into three contemporaneous rock units: limestone-conglomerate and shale; clastic rocks; and ophiolites. The ophiolites or "Upper Thrust Slices" represent oceanic crust and mantle that was emplaced during the Middle Ordovician (Malpas 1976:34). Most of the ophiolites from Humber Arm and Hare Bay are igneous and metamorphic rocks (Malpas 1976:36). The following is a detailed description of the outcrop areas under study.

3.3.1 Baie Verte Peninsula

The Baie Verte Peninsula is divided into two geological terranes by a northeasterly trending zone known as the Baie Verte Line. This major fault zone separates rocks of the Paleozoic margin of North America that incorporate the entire west coast of Newfoundland (Humber Zone) and the ancient Iapetus Ocean in central, interior Newfoundland (Dunnage Zone) (Hibbard 1983:17; Fig.3.2). The Peninsula is further divided into the Fleur de Lys Belt and the Baie Verte Belt based on the geologic division created by the Baie Verte Line. Fleur de Lys and the area around which this research is based are located in the Fleur de Lys Belt. The Fleur de Lys Belt is comprised of three stratigraphic sections: 1) ophiolitic basement; 2) volcanic cover sequences; 3) a variety of mafic to granite intrusions (Hibbard 1983:73). The basement rocks are the rocks under investigation here, and, in the town of Fleur de Lys, the metamorphic ultramafic rocks are discontinuous, sheared rock outcrops with a northerly trend. They are extensively metamorphosed and do not retain any characteristics of the original protolith; they have been entirely recrystallised to talc-carbonate-fuchsite schist or talc-carbonate-actinolite/tremolite schist variations (Hibbard 1983:57).

The Fleur de Lys Dorset soapstone quarry is comprised mainly of Localities 1 & 3 as delineated by Nagle (1982). These localities are part of one structural slice of metamorphosed rocks of ophiolitic origin present in the community of Fleur de Lys. The outcrop exhibits mineralogical variation throughout and two mineralogical signatures have been identified from a previous provenance study by Nagle (1982) using INAA.

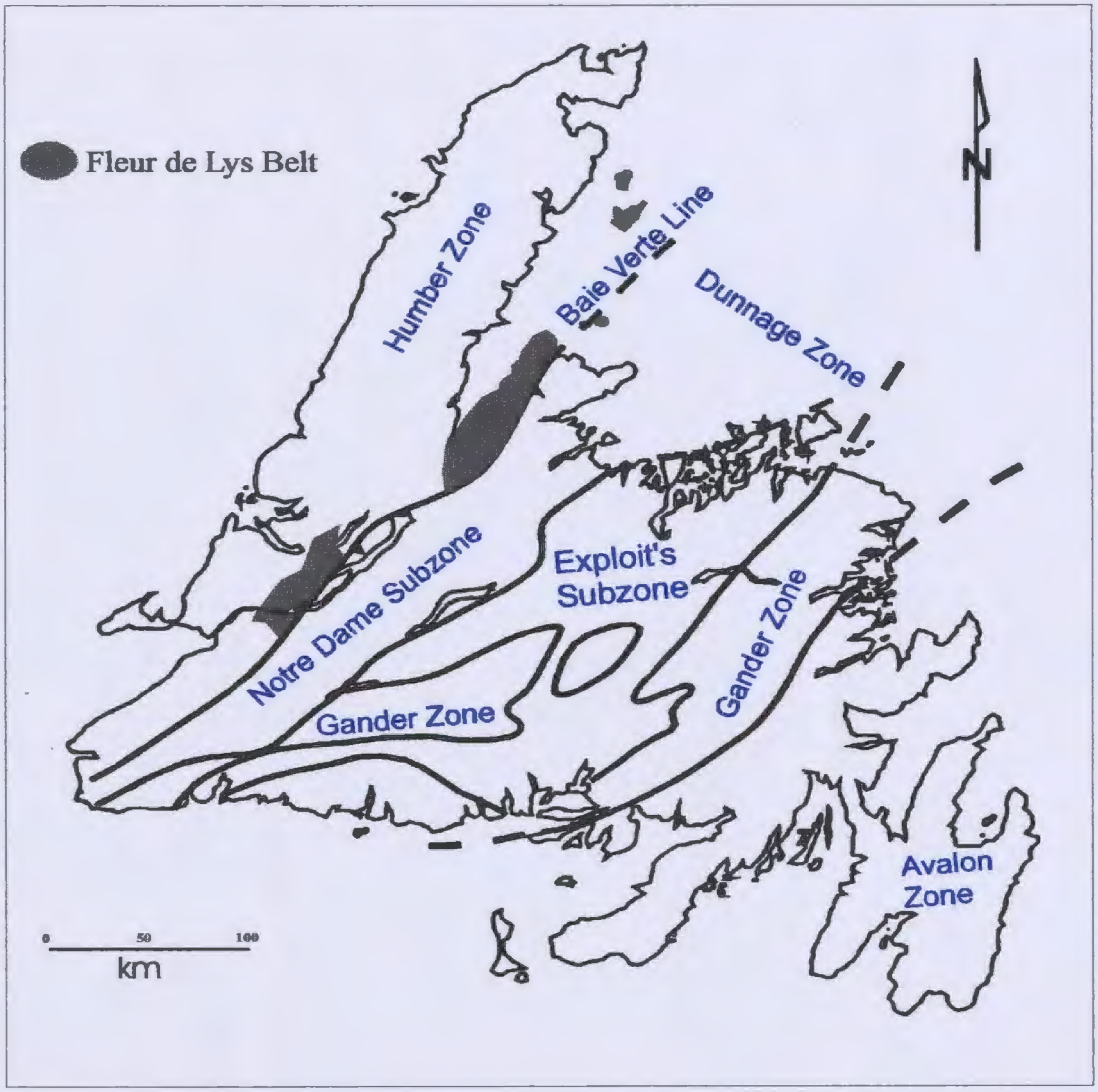


Figure 3.2: The major zones of the Island of Newfoundland (adapted from Williams et al. 1988 and Hibbard 1983:23).

3.3.1.1 Unit Description

Fleur de Lys soapstone has been weathered and an orange patina, up to two inches thick, covers the fresh green/blue rock surface. Soapstone that has been buried by soil formation retains the fresh surface of the rock outcrop. Large talc grains are visible along some areas of the outcrop (Fig.3.3). Five samples along the outcrop (Localities One and Three) were collected for study due to the heterogeneity of the rock mineralogy. In hand sample the fresh rock surface is defined mostly by talc but the fine-grained nature of the samples requires petrographic analysis and XRD for semi-quantitative mineral characterisation.

In thin section, most samples are comprised of a talc matrix, composing approximately 50% of the mineral assemblage while serpentine predominates in some of the rocks. Magnesite makes up the remainder of the assemblage (40%) and spinel occurs as a minor phase (i.e., 5-10%) (Figs.3.4; 3.5).

3.3.2 St. Anthony (Howe Harbour) Outcrop

The geological samples collected for this study from the St. Anthony area, at Howe Harbour on the Great Northern Peninsula, are from the White Hills Peridotite, a segment of the Hare Bay Allochthon. The stratigraphic profile of the allochthon consists of Middle Ordovician ophiolitic rocks and a metamorphic aureole located at the top of the allochthonous sequence, followed by igneous and metamorphic rocks, and Cambrian to Lower Ordovician sedimentary rocks at the base (Williams and Smyth 1983:109). A scarp delineates the western margin of the sequence and a low-lying ridge borders the rest

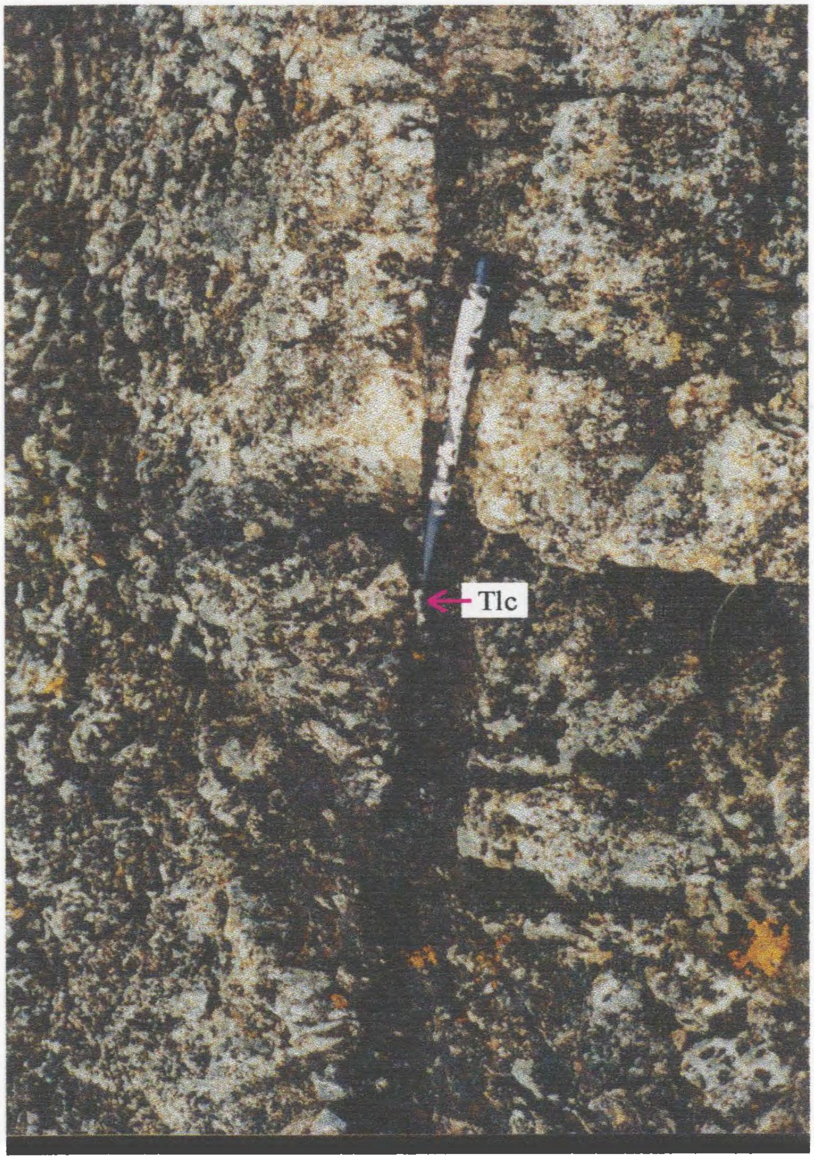


Figure 3.3: Large talc grain in the Fleur de Lys outcrop

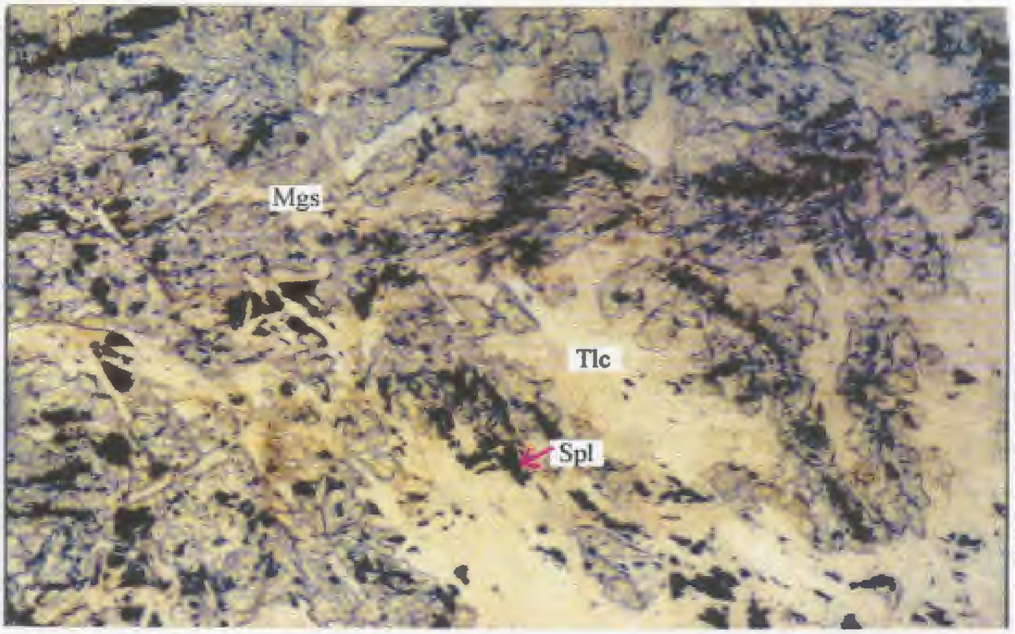


Figure 3.4: Outcrop sample Fdl-1 from the Fleur de Lys quarry, Locality One. Field of View = 1.5mm, ppl, 10x magnification.

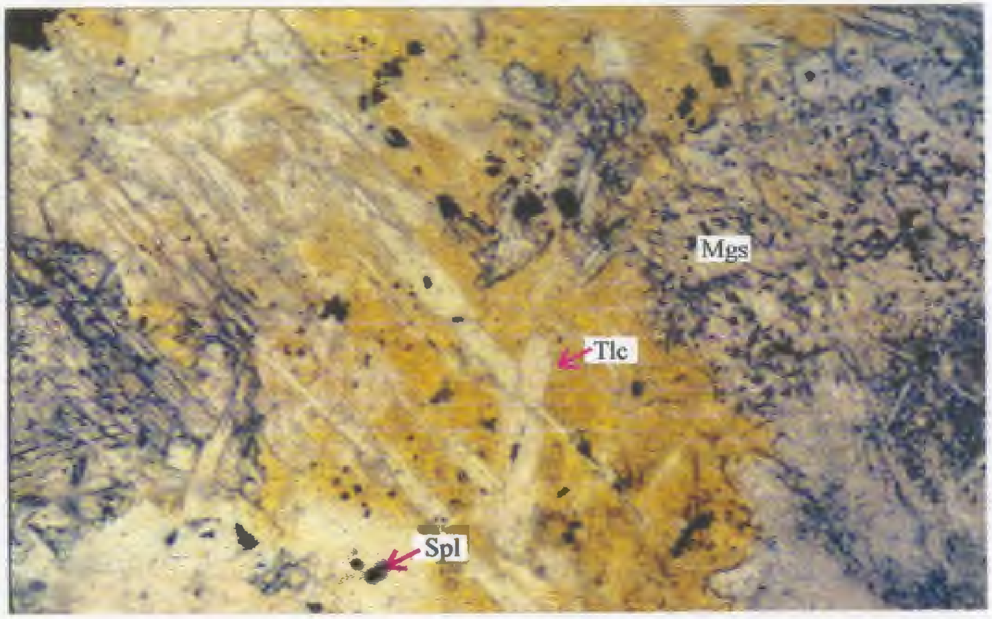


Figure 3.5: Photomicrograph of outcrop sample FDL-4 from Fleur de Lys quarry, Locality 3. Field of view = 1.5mm, ppl, 10x magnification.

of the allochthon (Williams and Smyth 1983:109). Six rock assemblages comprise the allochthon, one of which is the early Ordovician White Hills Peridotite, located on the northern coast of Hare Bay. Melange sections separate the allochthonous zones (Williams and Smyth 1983:110). Underlying the White Hills Peridotite are the Goose Tickle Formation, the Northwest Arm Formation, the Maiden Point Formation, Goose Cove Schist, and the Green Ridge Amphibolite (Talkington 1981). The Hare Bay Allochthon measures approximately 130 km north-south and 32 km east-west (Williams and Smyth 1983:109) and the White Hills Peridotite measures approximately 20 km long and 9 km wide trending east-west on the northern tip of the Great Northern Peninsula (Talkington 1981). The White Hills Peridotite outcrops as three massifs originally mapped by Talkington (1981). There are two characteristics of the White Hills peridotite that make it important for this research. The White Hills Peridotite is distinguished from other ophiolites, including the Bay of Islands Complex, in that only the ultramafic component of the ophiolite remains and a mixture of harzburgite and spinel lherzolite comprises almost 85% of the ophiolite (Talkington 1981:34). This is contrary to the "idealised" ophiolite stratigraphy (Talkington 1981:35-36) present to varying degrees in other ophiolites of west Newfoundland. The White Hills Peridotite is mantle that was transported and emplaced concurrently with the development of a continental margin during the Middle Ordovician (Talkington 1981). Following emplacement of the rocks another deformation event occurred causing folding, mostly south of Hare Bay.

The rocky beach surrounding the mouth of Howe Harbour is accessible by boat, located only a few hundred metres from the exposed peridotite. Erratics and glacial striations mark evidence of past glaciation with an east to southeast trend (Williams and

Smyth 1983:110). On the east side of Howe Harbour, banded ultramafic rocks occur at the base of the White Hills Peridotite. About 1.5 m of rock is exposed here, mostly in the form of small blocks of detached outcrop. Samples for this study were taken from outcrop along the west side of Howe Harbour, where large blocks also occur, along the base of Mount Mer.

3.3.2.1 Unit Description and Petrography

At Howe Harbour, the peridotite is primarily barren rock comprised of dunite, harzburgite (Williams and Smyth 1983:127), pyroxenite veins, and spinel lherzolite contained in layers throughout the rock (Talkington 1981:81). Talkington (1981:47) describes these layers as varying from 1 mm up to 50 cm in thickness, and they are inconsistent throughout the outcrop. An orange/brown weathering rind masks the fresh surface of the rocks.

In thin section, these harzburgitic rocks contain olivine (approximately 30%), orthopyroxene (approximately 20%), and serpentine (40%) with subordinate spinel (5-10%) (Fig.3.6). The first indication of alteration is apparent where serpentine is formed in the cracks along the margins of the olivine grains.

Olivine occurs as anhedral to subhedral grains and grain size varies from 0.5 mm to 1 mm. Talkington (1981:51) suggests that grain size of olivine is dependent upon the amount of deformation that has taken place. Orthopyroxene is colourless and grain shape is typically subhedral. Undulatory extinction is again ubiquitous. Spinel is present as small grains and comprises approximately 10% to 15% of the rock composition.

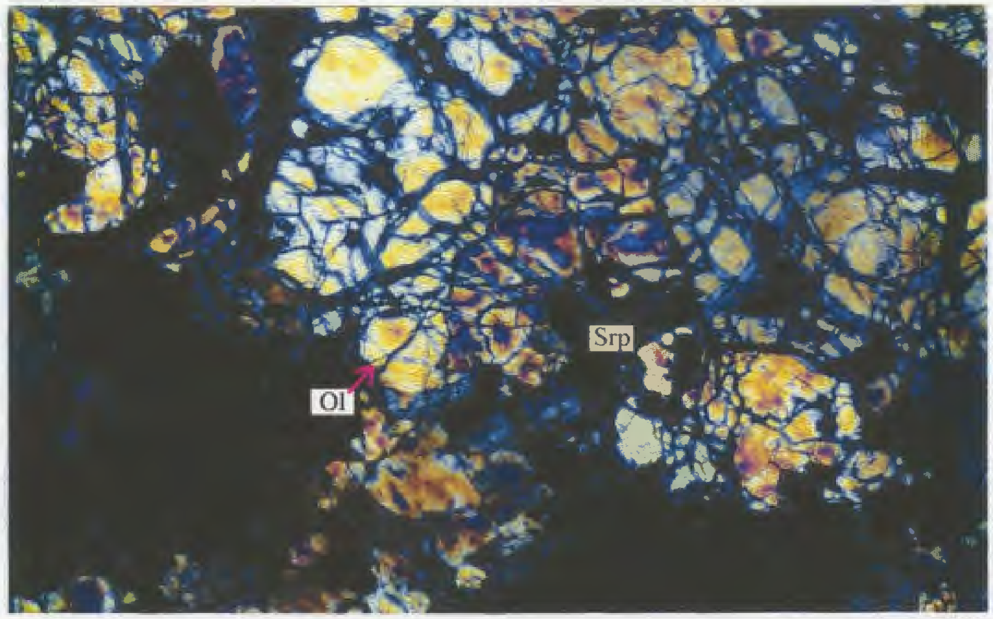


Figure 3.6: Outcrop Sample Anth 3 from St. Anthony (Howe Harbour). Field of view = 1.5mm, xp, 10x magnification

Serpentine forms along grain boundaries and at the expense of olivine and pyroxene. Individual grains are indistinguishable. In these samples, as well as those from the Tablelands and Trout River, I was unable to determine the texture(s) of the serpentine due to the extremely fine-grained nature of the serpentine grains. Texture can often be diagnostic of the protolith, whether a harzburgitic or dunite parent.

Using XRD analysis, the variety of serpentine present in these rock samples has been identified as lizardite. However, it is possible that remnant antigorite is also present in lesser quantities. Relict olivine, which is similar in composition to forsterite, is present in thin section but is not a significant mineral phase, and is not present in the XRD analysis. This indicates that serpentine has significantly replaced the primary minerals olivine and orthopyroxene.

3.3.3 Trout River (Gros Morne National Park)

Gros Morne National Park has a complex geological history and is recognised for its world-renowned landscape. It has thus been designated a World Heritage Site by UNESCO. Of the many natural attractions of Gros Morne Park is Trout River Pond, a fjord-like lake formed after glaciers from the Wisconsinian glaciation retreated (Burzynski 1990:48). Ophiolites comprise the rock assemblage south of Trout River Pond. Also, the Tablelands, which are the most significant feature of Gros Morne Park, extend along the shores of Trout River Pond on the north and south sides. The yellow-orange peridotite that forms the Tablelands is distinguished by the obvious lack of vegetation (Fig.3.7). This is a result of the chemical composition of the peridotite, which cannot support plant life. The Tablelands are often referred to as the "serpentine barrens"

Figure 3.7: The Tablelands outcrop. Lens cap is used for scale.

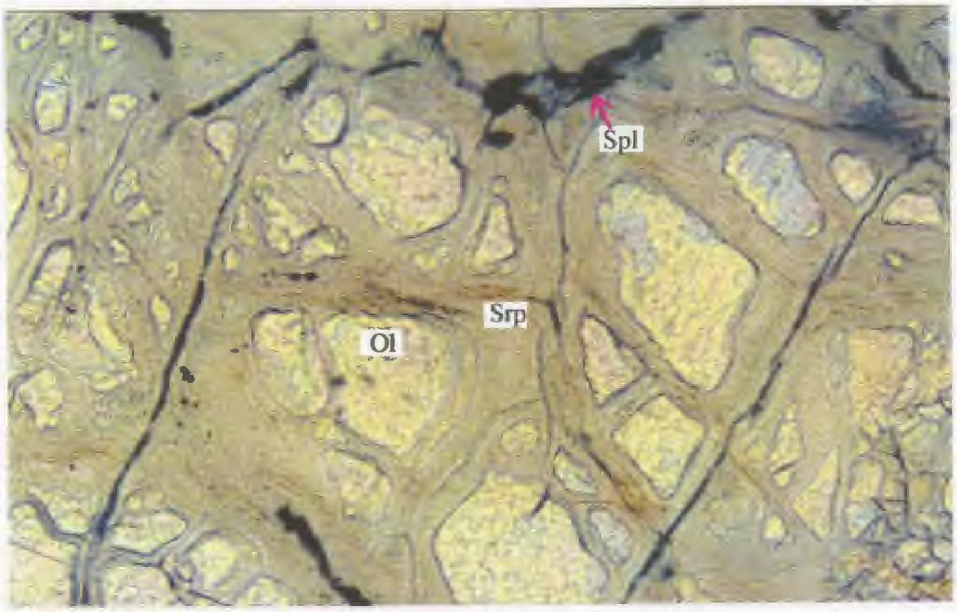


Figure 3.8: Outcrop sample TR2 from Trout River outcrop. ppl, 20x magnification.

with only low-lying "dwarf-scrub", cushion mosses, and unusual arctic-alpine plants, however, along Trout River Small Pond and Trout River Big Pond is a forest comprised of balsam fir, white spruce, and white birch (Berger et al. 1992). An established hiking trail along Trout River Big Pond/Small Pond extends through this forest and advances upon the exposed, barren peridotite.

The bedrock geology of the Tablelands and Trout River Big Pond/Small Pond area is composed of peridotite, part of the allochthonous igneous rock complex that originated from the ancient Iapetus Ocean (Berger et al. 1992).

3.3.3.1 Unit Description

The Tablelands peridotite has an orange/tan-coloured weathered surface that masks a green-brown fresh rock surface. These rocks have been altered through serpentinisation and the addition of elements to the rock has modified the mineralogy of the rocks. Olivine and serpentine comprise the major minerals, 35% and 30% respectively (Fig.3.8). Serpentine occurs along the margins of olivine and less than 20% of relict orthopyroxene remains. Spinel grains comprise approximately 5% of the overall assemblage. These peridotites are similar in composition to the rock outcrop at St. Anthony.

3.4 Summary of Chapter Three

The relationships of rock types within and between ophiolites in western Newfoundland figure prominently in this provenance study. The parental relationships between peridotite rock assemblages and soapstone are investigated here by using soapstone, an extensively altered ultramafic rock, and comparing it to less altered peridotite rocks from west Newfoundland. Petrography of peridotite rock outcrops from Trout River, Tablelands and Howe Harbour and soapstone samples collected from the Fleur de Lys quarry illustrate the range of alteration expected from both extremes of the alteration spectrum. Because soapstone is formed from peridotite by alteration by pressure and temperature fluctuations during metamorphism and the influx of CO_2 and H_2O during serpentinisation and carbonatisation, the original parentage of soapstone is often obscured by extensive mineral changes. The resulting rock has a talc-carbonate-dominated mineralogy.

The petrography shows that an olivine/serpentine/pyroxene/spinel assemblage is found in the samples from Gros Morne and from St. Anthony (Howe Harbour). Samples from Trout River and Tablelands and from St. Anthony (Howe Harbour) show early alteration indicated by serpentine forming along the margins of and at the expense of olivine. The outcrop samples from Fleur de Lys illustrate the result of extensive alteration. The primary mineral assemblage has been changed to a predominantly talc-carbonate assemblage from a peridotite protolith.

Timbal (1992:209) explains that the influx of water into the original peridotite will often replace olivine with pseudomorphic lizardite. Then the pseudomorphic textures after olivine are sometimes replaced by non-pseudomorphic antigorite (interpenetrating textures) or antigorite and/or lizardite (interlocking textures). Also, pyroxenes often become lizardite (Timbal 1992:209).

The XRD analysis of selected samples corroborates the petrographic data for the most part. Olivine and serpentine (primarily antigorite) are present in the samples submitted for XRD analysis from Howe Harbour and Trout River and the Tablelands. These samples have been partially serpentinised from their original peridotite composition but are considered harzburgites.

CHAPTER FOUR

MAJOR AND TRACE ELEMENT GEOCHEMISTRY

4.1 Introduction

The chemical compositions of artifacts and outcrops will be used to test for any link between artifacts and distinct outcrop areas and to compare artifacts to the Fleur de Lys quarry site. Major and rare earth element analyses of all samples were carried out using x-ray fluorescence (XRF) and inductively coupled plasma-mass spectrometry (ICP-MS) facilities in the Department of Earth Sciences, Memorial University. Details of the instruments and operating conditions are given in Appendix Two.

4.2 Rationale for Geochemical Applications and Data Quality Assessment

Due to the heterogeneous modal abundances of minerals in the rocks of interest, many issues had to be addressed prior to analysis. Not all trace elements are equally useful in the geochemical characterisation of these rocks. The most immobile elements (i.e., elements that do not move during fluid alteration) are the key to chemically characterising the soapstone. The immobile elements are indicators or relicts of the composition of the protolith, elements that resisted the effects of fluid alteration. Likewise, the concentrations of mobile elements in a rock may attest to the degree of metamorphism and the amount of alteration that has taken place. In each of these soapstone specimens, mineral assemblages are related to the degree of alteration and suitability to carve. For example, talc and serpentine, the minerals in soapstone that help give it the soapy-feel and the pliable characteristics carvers require, are secondary minerals formed by breakdown of the primary minerals. Because soapstone can contain any number of minerals in varying amounts, and is heterogeneous in nature, tracing the alteration history back to the original parental assemblage is difficult and in some cases impossible. Identifying and describing the mineralogy of these rocks was the first step in discriminating different rock outcrops and artifacts. However, it is the trace elements that provide information about the original chemical composition of the rocks and enable samples to be assigned a chemical signature, or fingerprint, such that artifacts or groups of artifacts can be compared to one another and to potential outcrop sources.

4.3 Trace Elements

Trace elements are elements in concentrations of less than 0.1 wt % or less than 1000 parts per million (ppm). They are typically studied in groups and tend to exhibit certain behaviours as a group. Any change from their characteristic behaviour can be an indication of certain petrological processes. The REEs are of particular geochemical interest and appear from atomic numbers 57 (La) to 71 (Lu) on the periodic table of the elements. Location (i.e., proximity) on the periodic table indicates these elements have similar chemical properties and are expected to demonstrate similar geochemical behaviour. For the purposes of this study, light rare earth elements (LREEs) include La, Ce, Pr, Nd, Sm, Eu and heavy rare earth elements (HREEs) are taken to mean Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu. The LREE and HREE may show different behaviour during fluid alteration of rocks, with the LREE being more mobile. High field strength elements

(HFSE) are a diverse group of elements with a wide range of incompatible and compatible behaviour in igneous rocks, yet they share the property that they are generally considered immobile or resistant to alteration by fluids. The HFSE include Sc, Y, Th, Zr, Hf, Nb, Ta, Ti, and the REEs (Jenner 1996:54).

Element mobility is common during hydrothermal alteration or metamorphism. It is therefore important when performing trace element studies to determine whether the elements tested were immobile during the pressure and temperature changes and fluid processes associated with hydrothermal alteration and metamorphism. Certain elements are known to be mobile or immobile and the immobile elements (i.e., the REE, HFSE, P, Co, Ni, V and Cr) are of particular interest. However, under conditions of very intense degrees of alteration, the concept of immobility is a relative one and it is possible that some of these typically immobile elements may become mobile under certain circumstances (e.g., carbonatisation). This will be discussed further in Chapter Five.

Rogers et al. (1983) conducted geochemical analyses of soapstone using neutron activation analysis (INAA) and have suggested that an accurate determination of the elements La, Sm, Eu, Gd, and Yb or Lu is satisfactory to characterise REE patterns of soapstone. The INAA method does not have sufficiently low limits of detection and therefore is of limited use in the analysis of rocks, such as soapstone derived from peridotites, with very low concentrations of REE (Jenner 1996). As seen in the following sections, ICP-MS has the capabilities to measure very low abundances of all of the REEs, yet even this more sensitive technique has problems for some of the REEs in some of the soapstone samples analysed in this study.

REEs are depicted on normalised plots so that the pattern is more easily discerned. The concentration of each REE in the sample is divided by the concentration of the same REE in the reference material. For this study all of the REE analyses of samples are normalised to primitive mantle (PM), which represents the composition of the earth's mantle that existed after core separation, but prior to crust/mantle differentiation (Jenner 1996:55).

4.4 Explanation of Geochemical Plots

The plots generated for this study are divided into major (per cent oxide), trace element (ppm) and PM- normalised REE diagrams. Major element plots reflect the major minerals present and are used to examine bulk rock composition, to examine the degree and style of alteration and are used to assign preliminary groupings based on general features of the samples. Trace element diagrams contain specific information about element behaviour and allow individual geochemical fingerprints to be identified so that samples can be grouped or differentiated from one another.

4.4.1 Major and Trace Element Plots to Distinguish Rock Units

Major element determinations were made using XRF pressed powder pellets (Appendix Two). Loss on Ignition (LOI) values were determined by pre-igniting the powders prior to producing the pressed pellets for the XRF. LOI represents the amount of mass of a sample that is lost (i.e., volatiles) after heating the rock powder to 1050°C and thus, the major elements are reported on a volatile-free basis (Tables 4.1 & 4.2). The samples analysed in this study primarily consist of silica (SiO_2) which comprises 33.9-58.9 wt% and magnesium (MgO) between 33-53 wt% of the rock (Tables 4.1 & 4.2). Other major elements include Al_2O_3, CaO, Fe_2O_3 below 10 wt% of the rocks and TiO_2, MnO, Na_2O, K_2O, P_2O_5 typically below 1 wt%. The 'major element plots' plot MgO and Al_2O_3 versus trace elements such as chromium (concentrations between 430 to 4262 ppm), strontium (varies from 1 to 309 ppm) and nickel (1025 to 3188 ppm). Ni and Cr vary above and below the concentration that is said to divide "major" from "trace" elements and are used here to represent bulk rock patterns.

Variations in abundances of major elements such as MgO and Al_2O_3, and trace Cr, reflect variations in the abundances of the main minerals present in the outcrop and artifact samples. MgO reflects the amount of talc, serpentine, chlorite and magnesite (all derived from alteration of original olivine) that comprise soapstone, whereas Al_2O_3 reflects the abundance of chlorite, and Cr reflects the abundance of spinel present. The ternary diagram Cr-Al_2O_3-MgO (Fig. 4.1) shows that the artifacts fall into 2 broad groups with some variation in each group. The Port au Choix and Cape Ray samples are distinct from all other artifact samples based on their higher aluminum content. Samples from outcrops plotted on the same ternary diagram (Fig. 4.2), shows that St. Anthony samples are clearly distinct from all other outcrop samples in that they have a higher proportion of aluminum as well as higher absolute concentrations (1.1-1.7 wt% Al_2O_3 vs. 0.3-0.5 wt%).

On a ternary diagram of MgO-Ni-Sr (Fig. 4.3; Fig. 4.4), the MgO represents abundances of talc, serpentine and magnesite, whereas Ni is mostly in spinel, and Sr is likely present in magnesite. A mobile element, such as Sr, can be used as an index of the

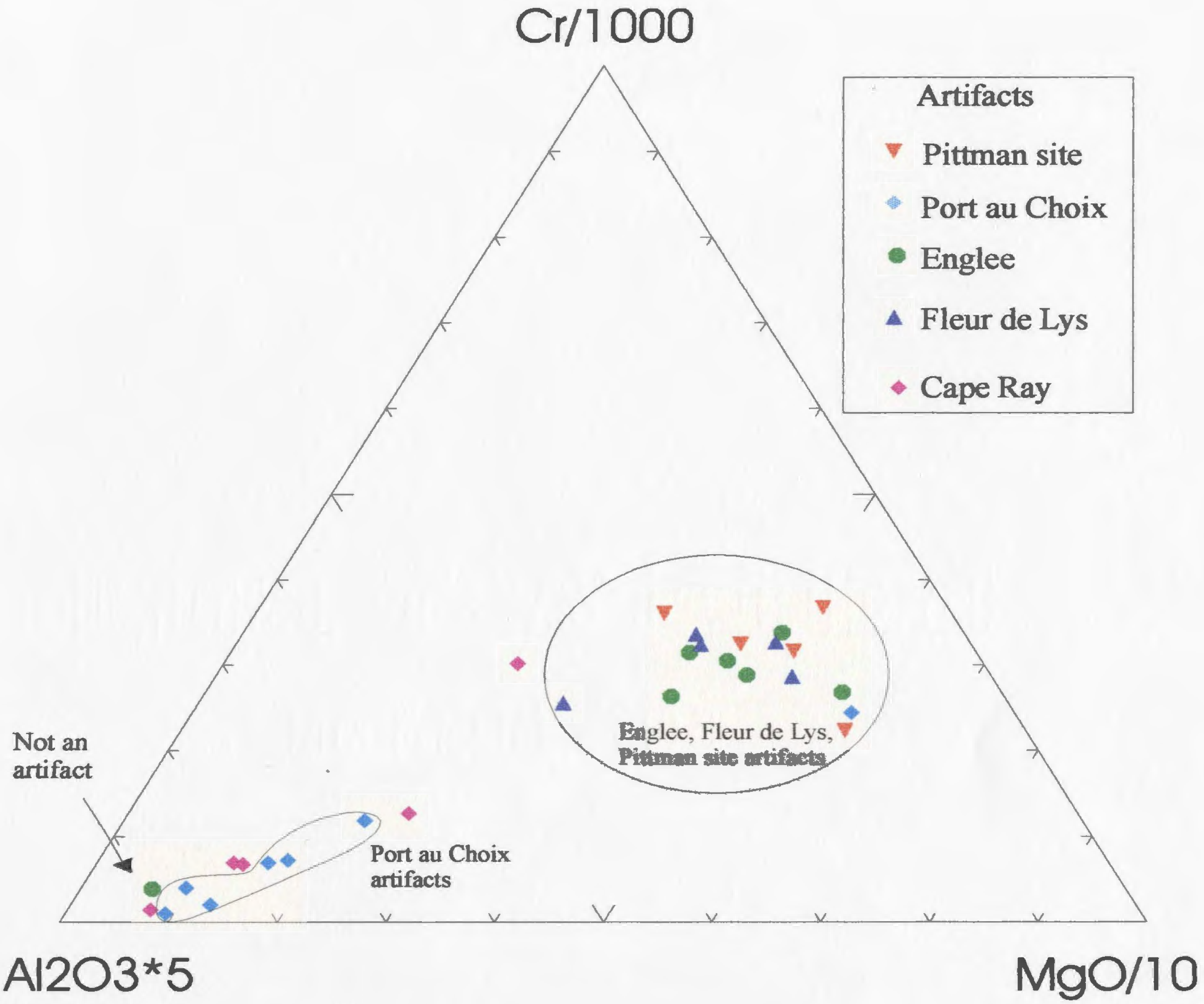


Figure 4.1: Ternary diagram illustrating concentrations of Al_2O_3 (wt %, concentration multiplied by 5), Cr (ppm, divided by 1000) and MgO (wt %, divided by 10) in all artifacts. Artifacts from Port au Choix and Cape Ray are aluminum-rich and are clearly distinctive from Fleur de Lys, Pittman site, and Englee artifacts which contain higher concentrations of chromium and magnesium (Englee sample E682 is not an artifact).

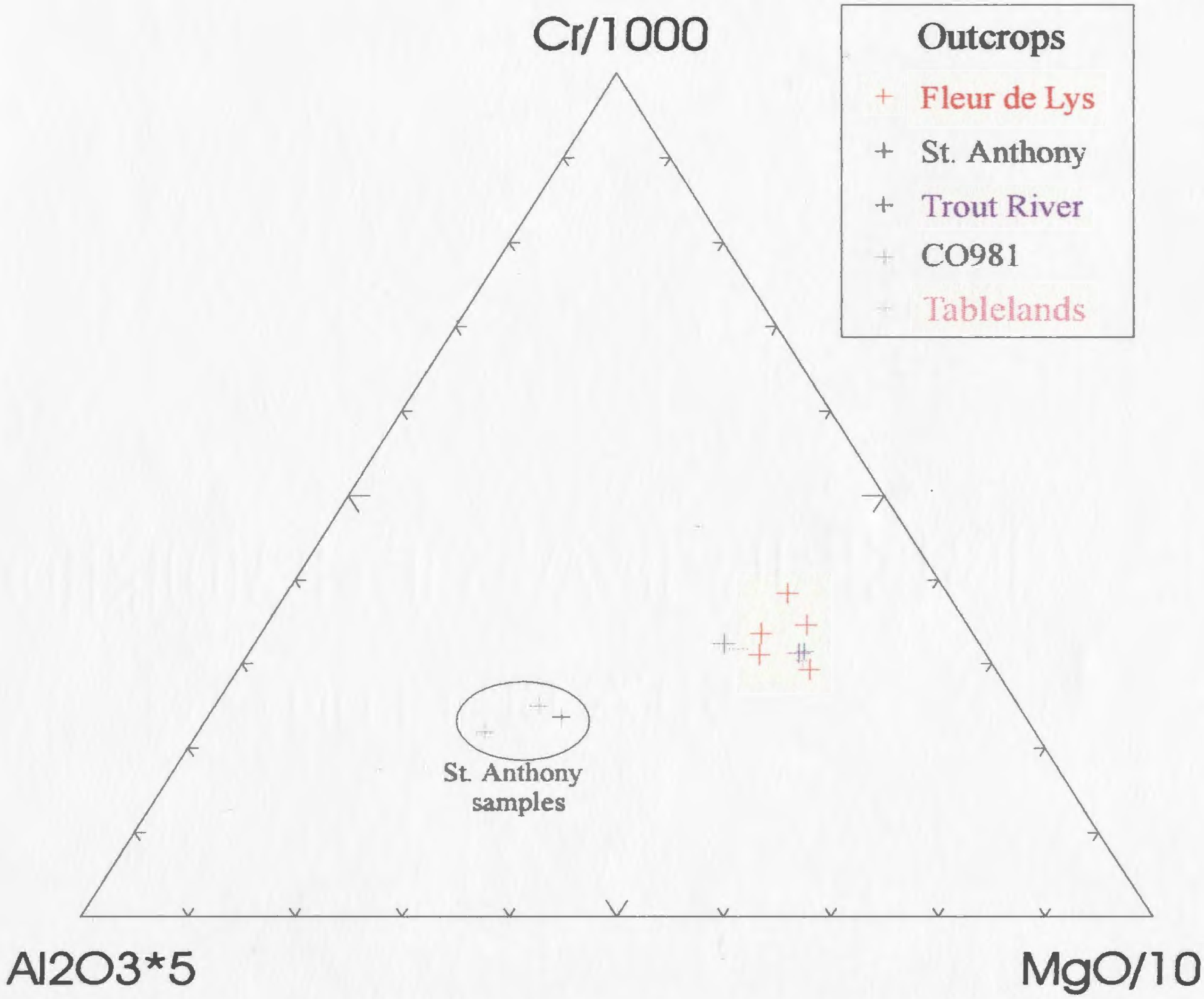
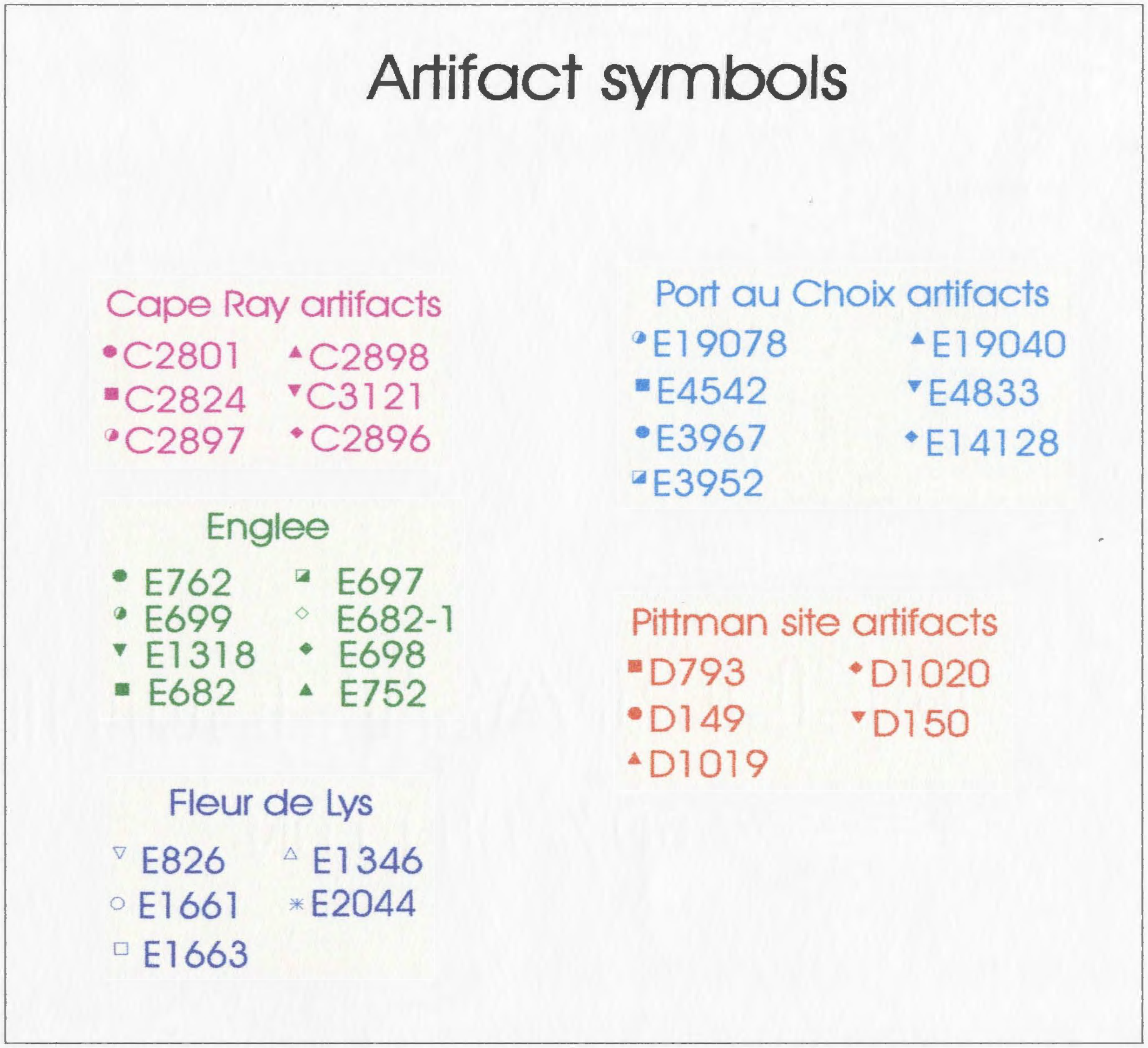


Figure 4.2: Major element diagram of outcrop samples. St. Anthony rock samples contain more aluminum than all other outcrops. Fleur de Lys, Trout River, CO981 Bear Cove Road, and Tablelands all contain similar concentrations of chromium and magnesium to the artifact samples (see fig. 4.1).



Artifact symbols

Cape Ray artifacts
●C2801 ▲C2898
■C2824 ▼C3121
◑C2897 ◆C2896

Port au Choix artifacts
◑E19078 ▲E19040
■E4542 ▼E4833
●E3967 ◆E14128
◪E3952

Englee
● E762 ◪ E697
◑ E699 ◇ E682-1
▼ E1318 ◆ E698
■ E682 ▲ E752

Pittman site artifacts
■D793 ◆D1020
●D149 ▼D150
▲D1019

Fleur de Lys
▽ E826 △ E1346
○ E1661 * E2044
□ E1663

Figure 4.3: The above artifact symbols and colour scheme are used for figures 4.4 to 4.19).

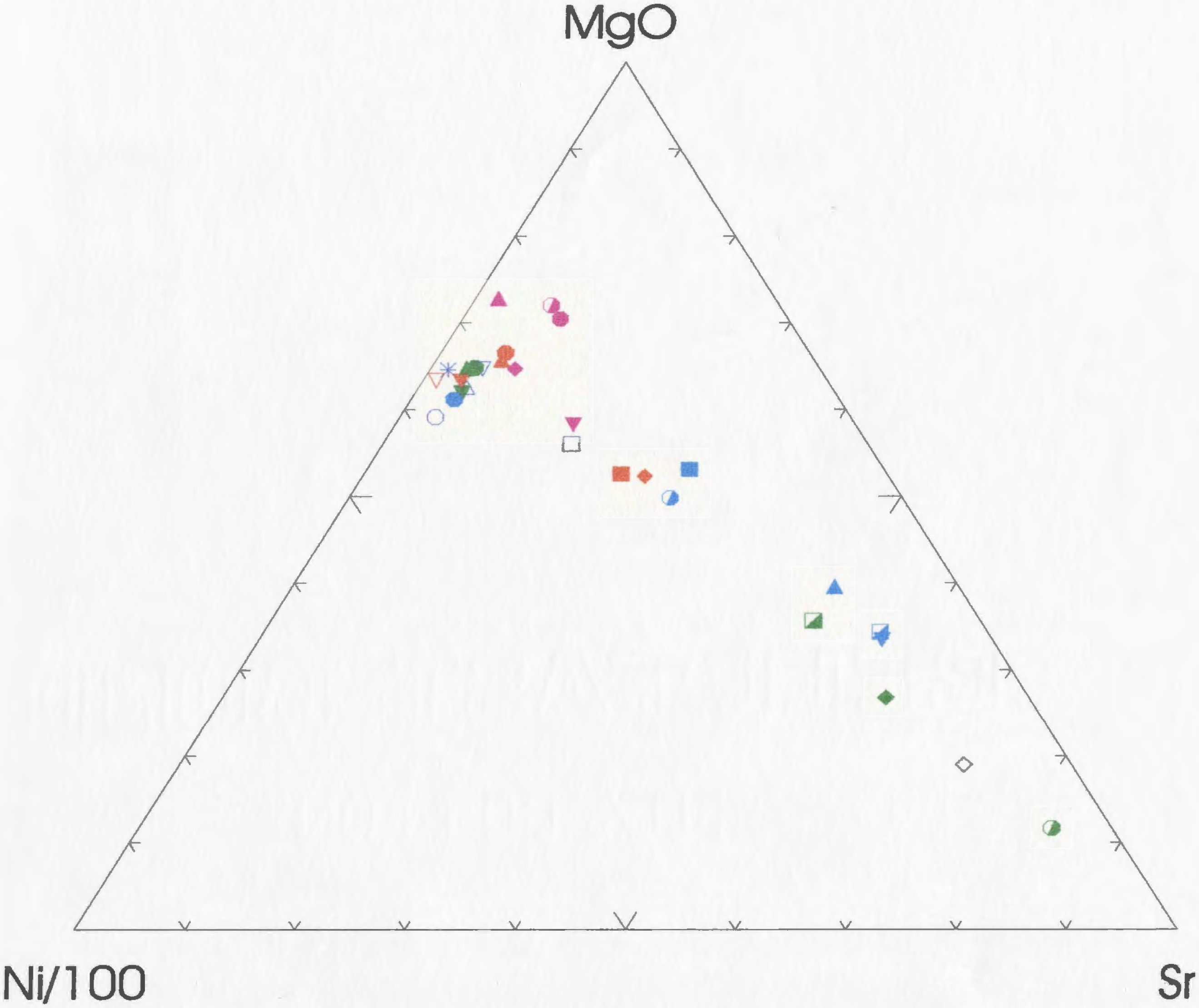


Figure 4.4: Ternary diagram illustrating concentrations of Ni-MgO-Sr. A high concentration of strontium reflects high carbonate content and indicates a possible post-depositional Sr event following use of the artifacts.

degree of alteration in a rock. High levels of strontium may indicate increased carbonatisation (i.e. alteration) or Sr addition via near-surface weathering (i.e. during burial of artifacts). It is apparent that the Englee and Port au Choix artifacts are significantly enriched in Sr and may represent a different alteration history compared to the other artifacts. The outcrop samples have broadly similar Ni, MgO, and Sr abundances (Fig. 4.5) though the St. Anthony and Bear Cove Road samples contain slightly elevated strontium. In this instance, increased strontium may be a primary igneous feature of this mantle rock in the St. Anthony area. All outcrop samples have a similar narrow range of MgO-Ni ratios. This ratio is likely a reflection of a primary igneous composition that has been largely preserved during alteration and metamorphism.

Ba, Sr and Rb are elements whose concentrations can be easily modified by fluid alteration. The alteration minerals that form soapstone also contain volatiles (e.g. H_2O and CO_2) that are represented in the chemical analysis as per cent loss on ignition (LOI). In this study, LOI varied from near 5 to 21% (mean 12%) for outcrop samples, and from 5 to 26% (mean 17%) for artifact samples. In theory, increased intensity of alteration should produce higher LOI and higher Rb, Sr and Ba concentrations. But the amount of increase depends on the specific alteration minerals. For example, talc has a 4-5 wt% H_2O, chlorite and serpentine 10-14 wt% H_2O, and magnesite near 50% CO_2. On a LOI-Sr diagram (Fig. 4.6a&b), the majority of artifacts have much greater Sr concentrations compared to most of the outcrop samples, suggesting the artifacts are more strongly altered, but there is a wide range of LOI values for artifacts and outcrops. The Cape Ray artifacts have notably lower LOI values (4-9 wt%) which suggests these have lower per cent abundance of

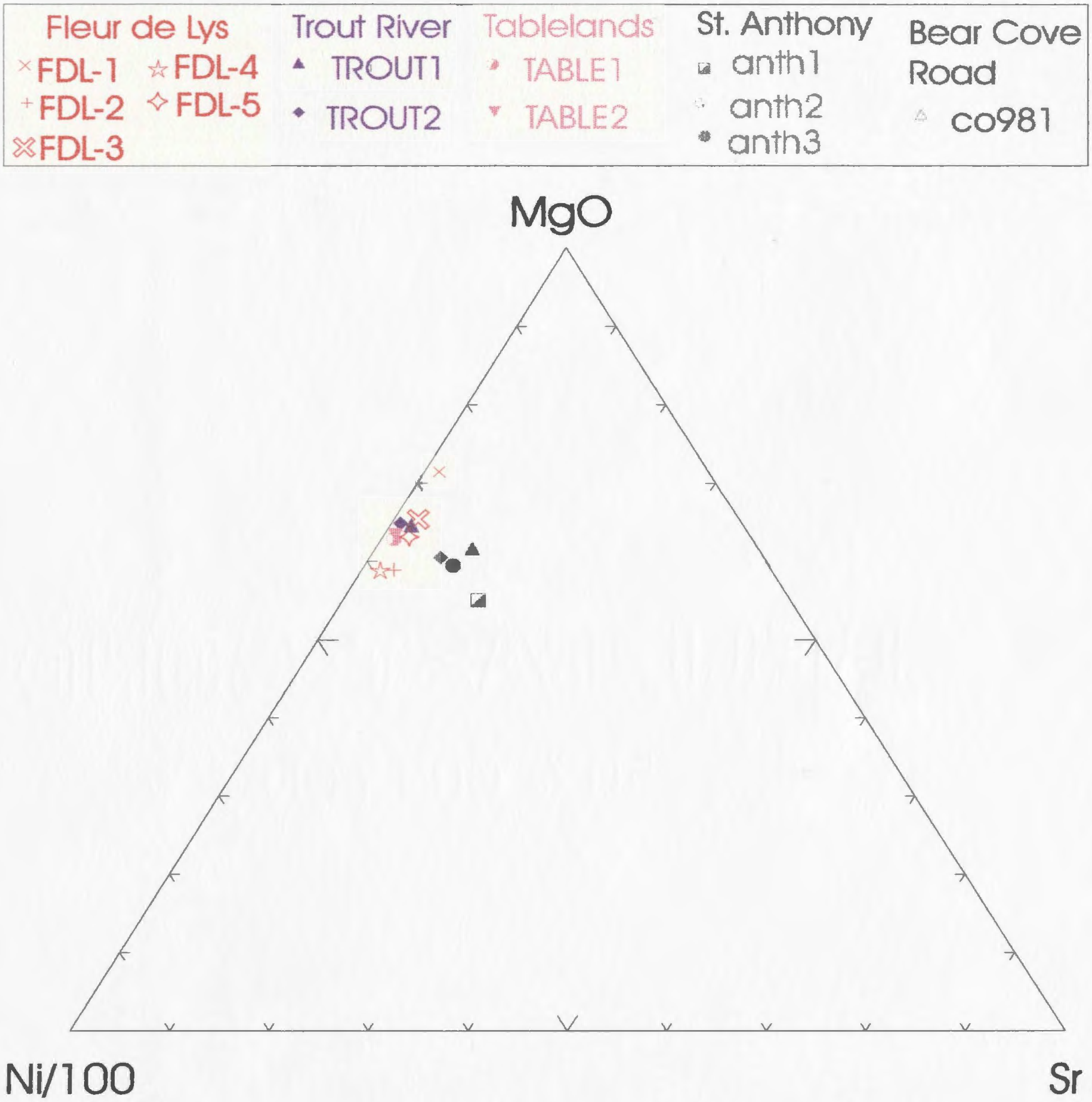


Figure 4.5: Ternary diagram illustrating concentrations of nickel, magnesium and strontium in outcrop samples. All outcrops have approximately the same proportion of nickel to magnesium but samples from St. Anthony contain more strontium. Higher concentrations of strontium reflect primary igneous features.

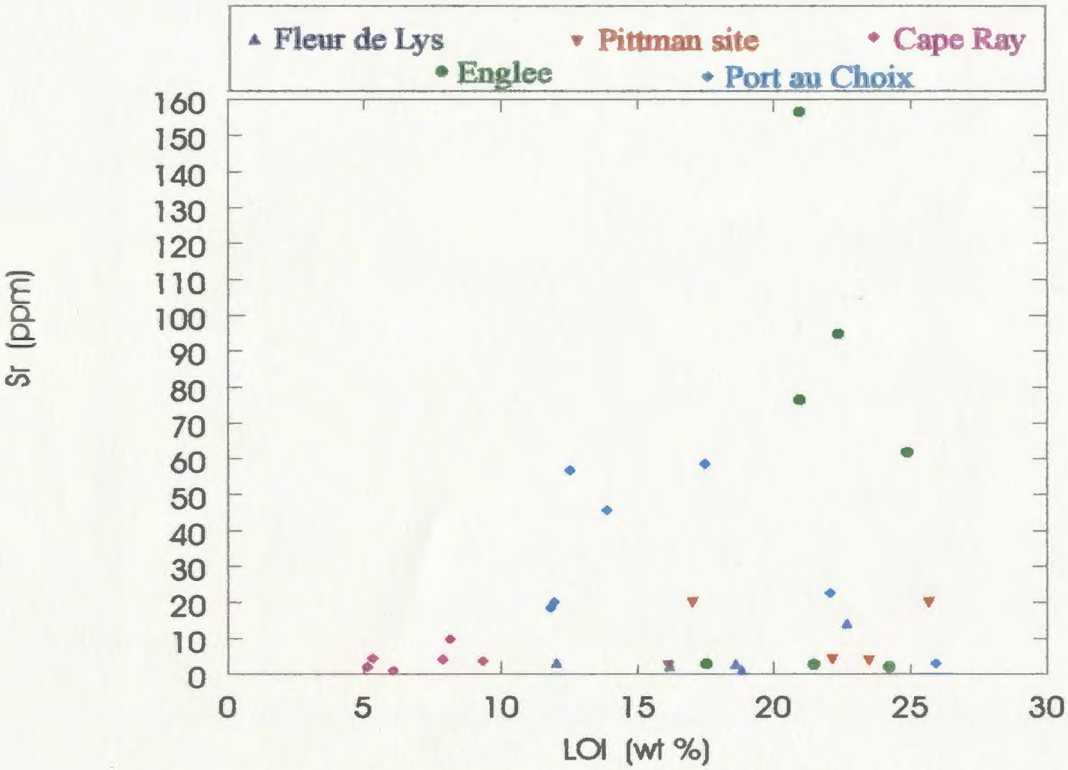


Figure 4.6a: Plot comparing Strontium concentration to Loss on Ignition values for all artifacts.

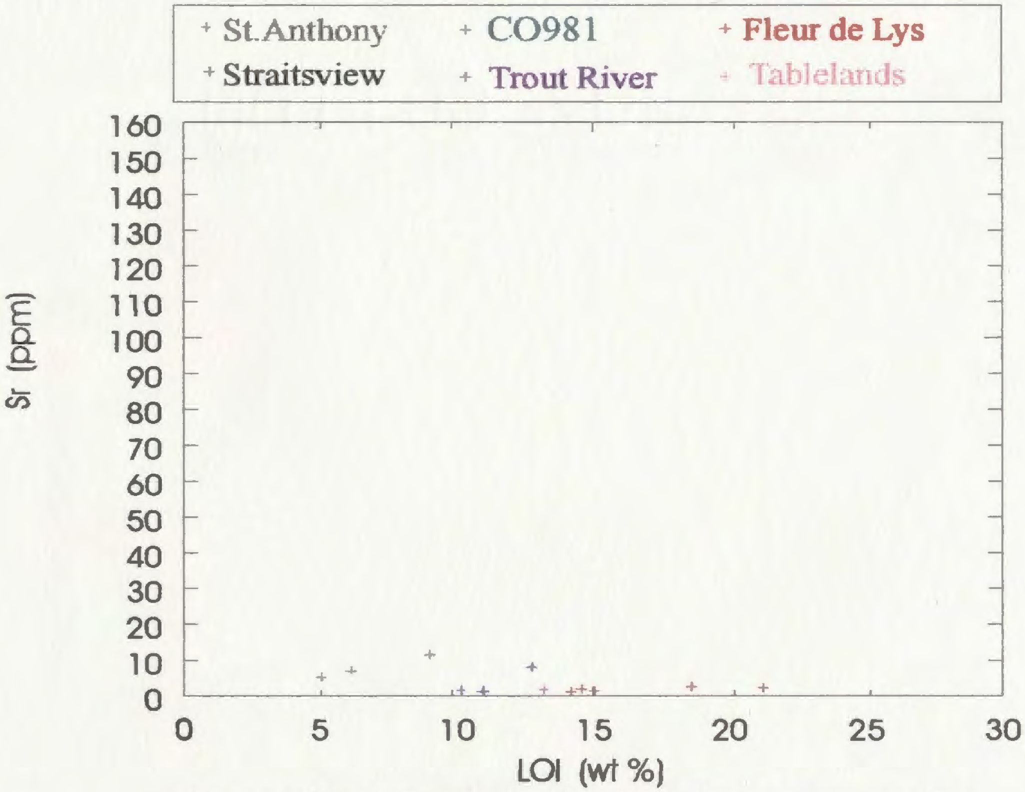


Figure 4.6b: Plot comparing Strontium concentration to Loss on Ignition values for all outcrop samples.

magnesite compared to other artifacts.

Alteration of talc to produce magnesite (carbonate) results in excess SiO_2 being released via the reaction:

$$\underset{\text{talc}}{Mg_3Si_4O_{10}(OH)_2} + 3CO_2 = \underset{\text{magnesite}}{3MgCO_3} + \underset{\text{quartz}}{4SiO_2} + H_2O$$

(Greenwood 1967; cf. Timbal 1992:235)

On a LOI -SiO_2 diagram for the Fleur de Lys artifacts and outcrops (Fig. 4.7), the artifacts have elevated LOI and SiO_2 values compared to outcrop samples. This is consistent with the artifacts being more intensely altered (carbonate-rich) than the outcrop samples.

4.4.2 Extended Rare Earth Element Geochemistry

There are 15 rare earth elements of which La is the first on the periodic table, and Lu is the last. The ratio of La over Lu provides information about the overall behaviour of the REEs as a group. La/Lu versus MgO can be used for defining preliminary groups of artifacts (Fig. 4.8). The Port au Choix artifacts have a low La/Lu value (3 +/- 2) and lower magnesium contents (36 +/- 3) with one anomalous sample having a MgO value near 47%. Cape Ray artifacts also have lower magnesium content but intermediate La/Lu ratios (10 +/- 4). Englee and Pittman site artifacts have higher magnesium contents (43 +/- 3) and somewhat different La/Lu values (2 +/- 1 and 5 +/- 3, respectively). The Fleur de Lys artifacts have fairly constant MgO (43 +/- 3) but the most widely variable La/Lu ratio (1.5 to 14.5), which suggests different populations may exist within this group.

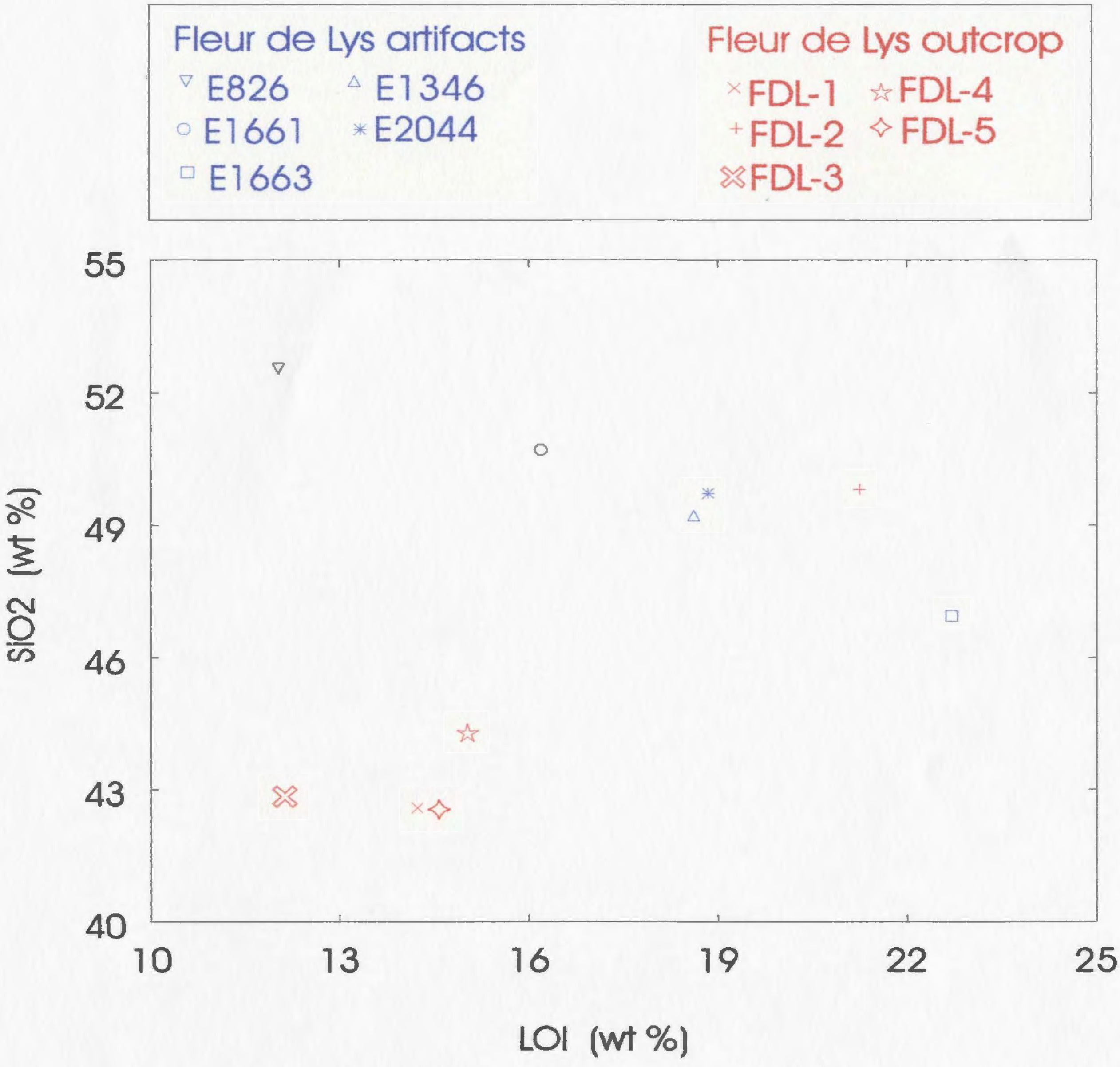


Figure 4.7: Concentrations of SiO2 versus LOI values for Fleur de Lys artifacts and outcrop samples.

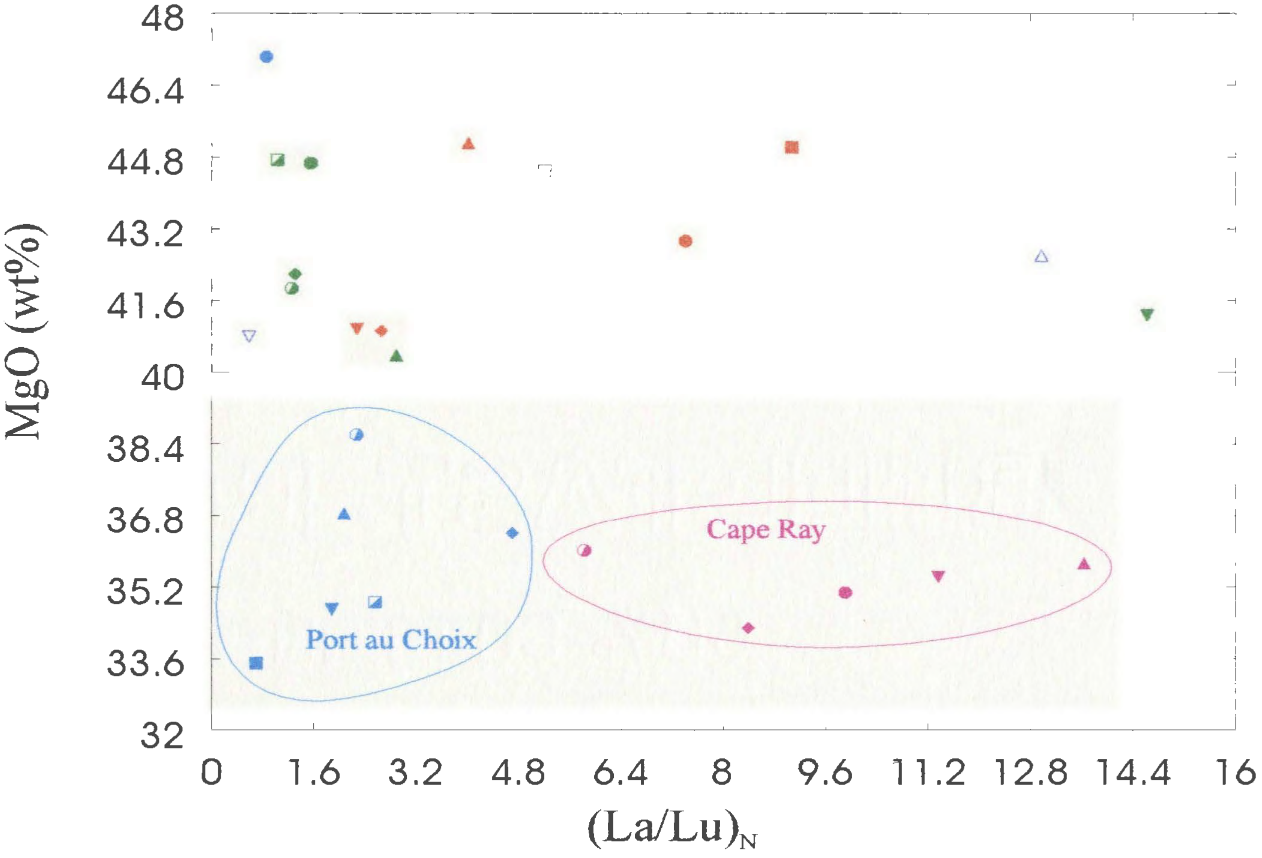


Figure 4.8: Ratio diagram of artifacts comparing MgO (wt%) to La over Lu. Port au Choix and Cape Ray are generally less magnesium-rich than the other artifacts. Englee artifacts have a low La/Lu ratio and more magnesium. Fleur de Lys artifacts have a widely varied La/Lu ratio.

Elements used for REE plots include most of the group from La to Lu as well as Th and Nb, which are useful additional immobile trace elements. For the following plots, the rare earth elements that were below the detection limits of the ICP-MS are excluded from the diagrams and subsequent interpretation (see data tables 4.1 and 4.2). Their exclusion results in incomplete REE patterns for some samples.

Interpretations of REE data are presented in three sections: 1) all artifacts from each Dorset site are compared to Fleur de Lys outcrop samples because Fleur de Lys is the only known Dorset soapstone quarry in Newfoundland; 2) REEs of artifacts recovered from sites likely to have been quarried from Fleur de Lys are compared to one another (e.g., Fleur de Lys and the Pittman site), and those artifacts considered not to have originated from the Fleur de Lys quarry (e.g., Port au Choix) are compared to Fleur de Lys artifacts, and; 3) a comparison is presented of all outcrop samples collected.

Primitive mantle normalised REE diagrams are used because they portray the REE data as fairly simple coherent trends on the diagrams. Whether these trends are linear, U-shaped or L-shaped, or whether they are located higher or lower on the diagram, reflect petrologic information that can be used to "fingerprint" groups of samples for comparison to other groups. When the REE patterns (trends) are fairly linear, it is possible to discuss the slope of the pattern as being diagnostic. When a particular element plots below its neighbours on the REE diagrams, this is called a "negative anomaly"; likewise, when an element plots above its neighbours it is called a "positive anomaly".

4.4.2.1 A Comparison of REE Patterns in Artifacts versus Outcrops

In this study, there are between 5 and 8 artifacts from each site and REE patterns for each group of artifacts can be compared to those of outcrop samples from the Fleur de Lys quarry. Samples can be characterised based on the shape and slope of their patterns and their abundances of REEs, and it can then be determined by the match or mis-match of patterns, which artifacts may have originated at one of the quarry localities at Fleur de Lys.

When the REE patterns of Cape Ray artifacts are compared to those of Fleur de Lys outcrop samples on a PM normalised diagram (Fig. 4.9), it can be seen that the Cape Ray artifacts exhibit very different trends from the Fleur de Lys outcrop samples. The Cape Ray artifacts have an order of magnitude enrichment in Th, Nb and LREEs compared to the outcrop samples, and four of the six artifacts have a significant negative Nb anomaly compared to no anomalies for the outcrops. Moreover, the shape or trend of the REE patterns are slightly U-shaped for the outcrops and more linear (positive slope) for the artifacts.

Some of the artifacts and outcrop samples have positive and negative Eu anomalies (Fig. 4.9). Eu is the only REE that changes its oxidation state (+2 or +3) and this phenomena can produce spurious enrichments or depletions in Eu. Therefore, Eu is not a reliable indicator of provenance (i.e., cannot be used to "fingerprint" groups).

When Englee artifacts and Fleur de Lys outcrop samples are compared on a PM normalised REE plot, the two groups mostly exhibit different trends (Fig. 4.10). There are some overlapping samples including E762, E697, E698 with FDL-4 and FDL-5, but the artifacts have a negative Nb anomaly not seen for the outcrops. All of the Englee artifacts

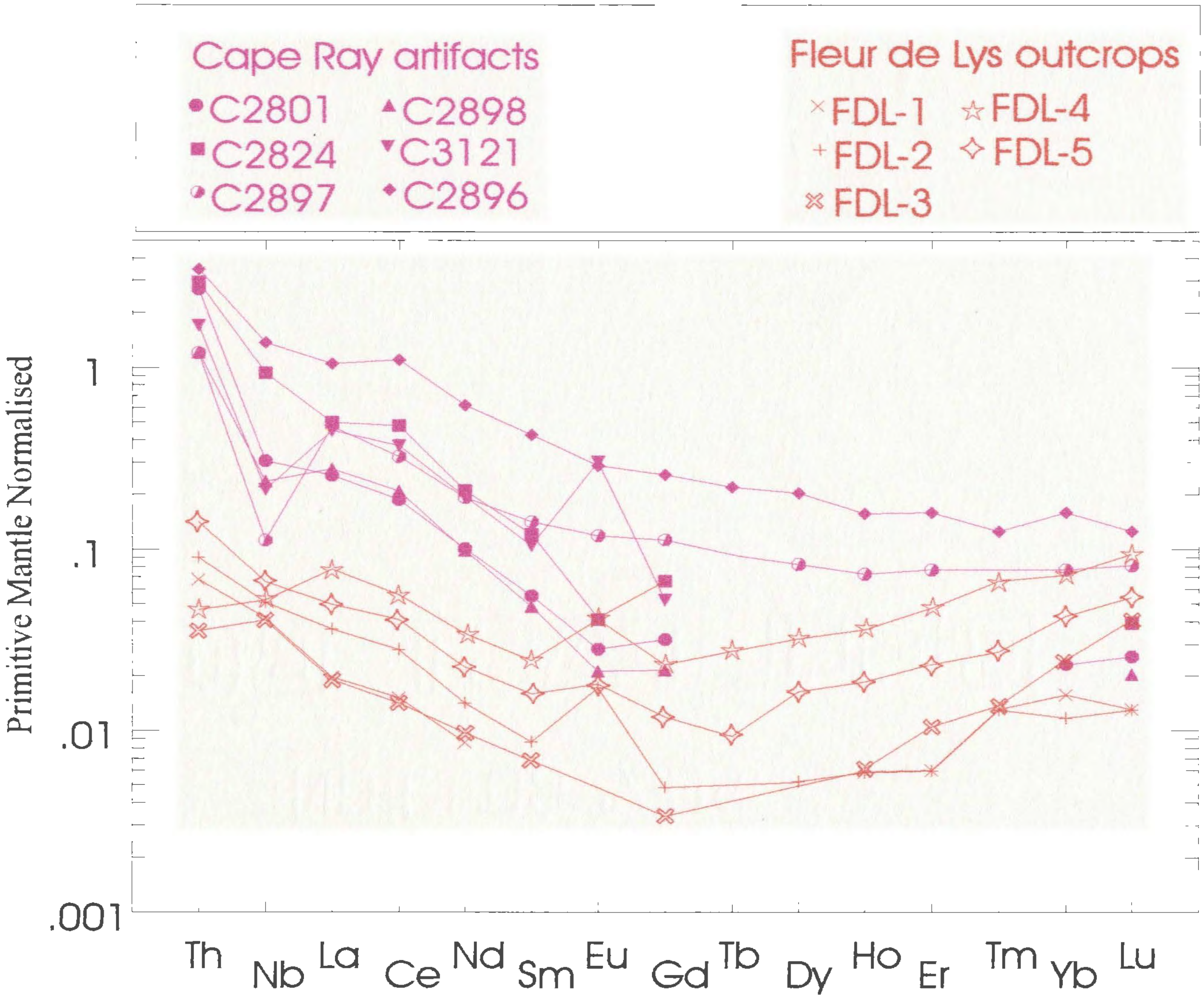


Figure 4.9: Primitive mantle normalised REE diagram comparing Cape Ray artifacts with Fleur de Lys outcrop samples. The REE patterns are very different for these two sites: Cape Ray exhibits LREE enrichment and a slight to prominent negative Nb anomaly not seen in samples from Fleur de Lys. The slope of the HREE are opposite as well.

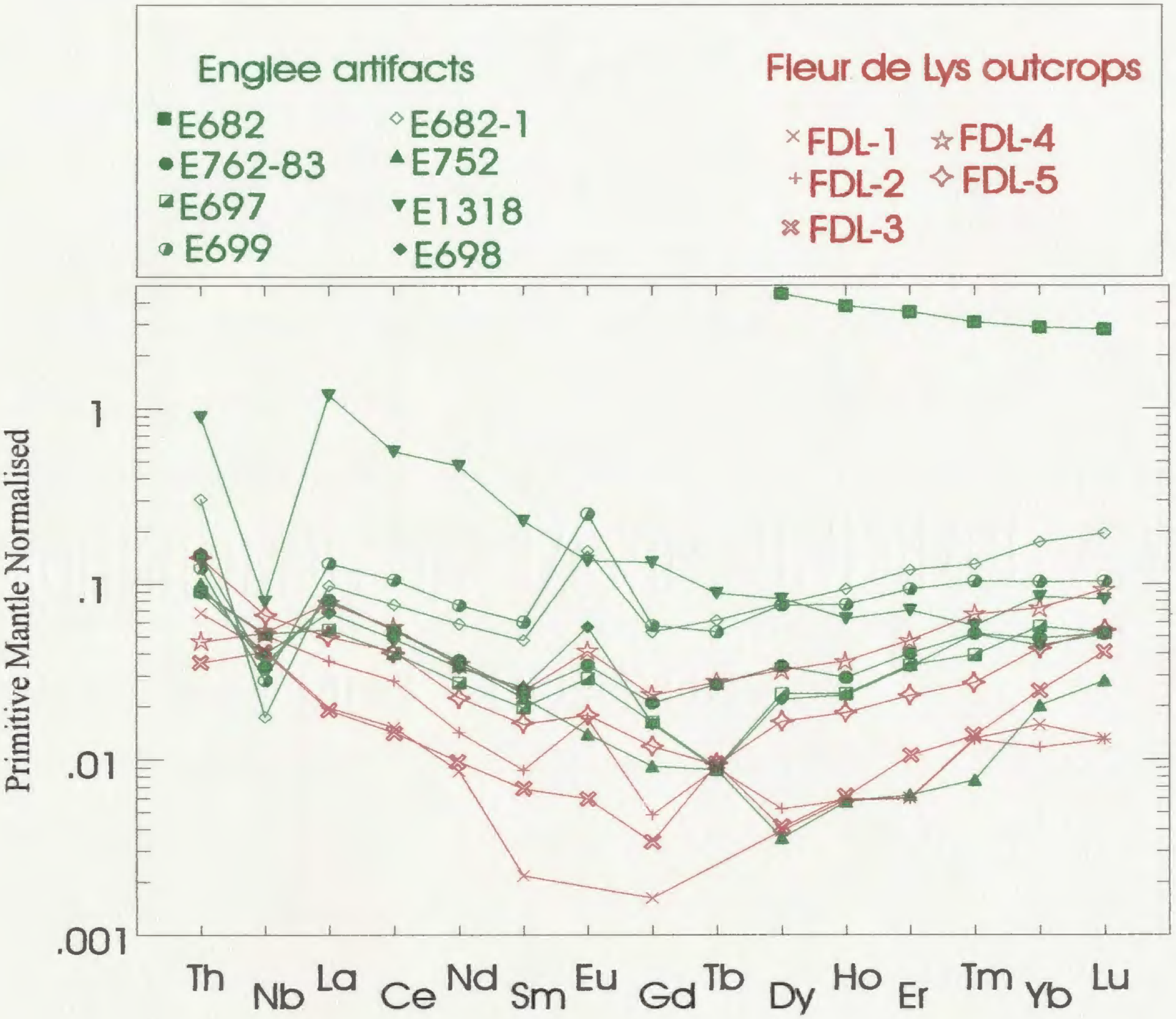


Figure 4.10: Primitive mantle normalised REE plot of Englee artifacts versus Fleur de Lys outcrop samples. All HREEs have a relatively flat pattern while the LREEs are enriched in the Englee artifacts. However, the HREEs are a better measure of REE concentrations in this study. Overlapping samples include E762, E697, E698 with FDL-4 and FDL-5. FDL-4 and FDL-5 were sampled from Locality 2 at Fleur de Lys and not from the main quarry face (i.e. Locality 1).

and outcrop samples share a generally U-shaped pattern except for artifact E1318 which has a positive slope, linear trend, enriched in LREE compared to the other artifacts. Englee sample E682 is enriched by almost two orders of magnitude in all elements (the pattern is truncated on the diagram), suggesting this sample is not an artifact (see petrography Chapter Two).

When REE contents of Fleur de Lys artifact and Fleur de Lys outcrop samples are compared on a primitive mantle normalised REE diagram, it is apparent that they do not exhibit the same REE patterns (Fig. 4.11). The artifacts have a significant negative Nb anomaly not present for the outcrops, and some have significant enrichments in the LREE. The difference between the artifacts and outcrops is an unexpected result since both groups were collected in reasonable proximity (several metres). The explanation is related to the relative intensity of alteration and the enrichment in the artifacts of "normally" immobile elements.

The Pittman site artifacts, when compared to the Fleur de Lys outcrop samples on a normalised REE plot, show broadly similar HREE patterns (Fig. 4.12). However, the artifacts are enriched in Th compared to the outcrops, and have a pronounced negative Nb anomaly similar to the artifacts from Fleur de Lys. The REE chemistry of the Port au Choix artifacts compared to Fleur de Lys outcrop samples reveals very different patterns (Fig. 4.13). The Port au Choix artifacts are enriched in Th and have flat REE patterns compared to the U-shaped patterns for the Fleur de Lys outcrops. Six of seven artifacts have a pronounced negative Nb anomaly. Artifacts E4833 and E4542 are very similar and came from a rock source distinct from the other artifacts at Port au Choix.

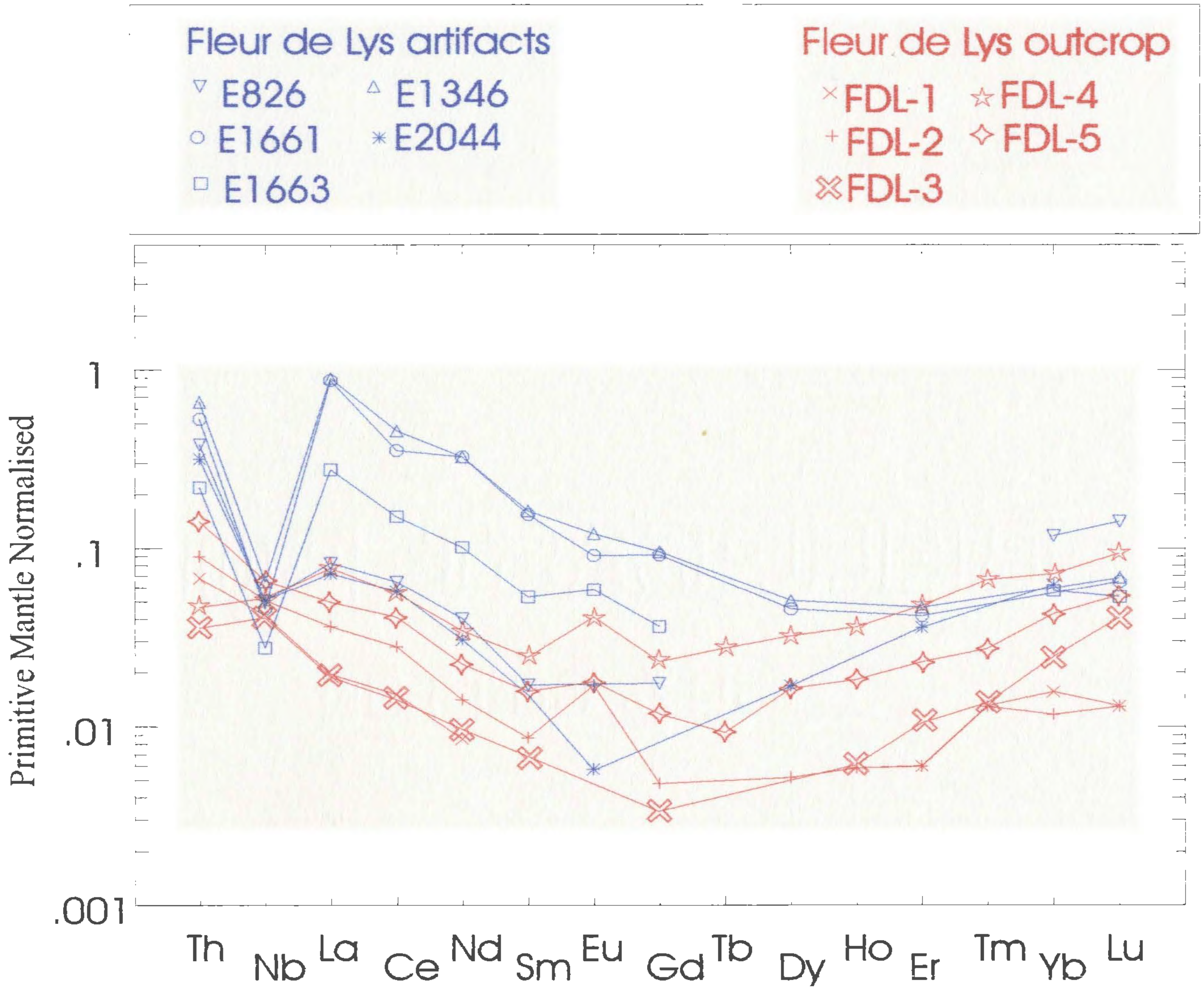


Figure 4.11: Primitive mantle normalised diagram of Fleur de Lys artifact and outcrop samples. The artifacts have a different REE pattern than the outcrop samples. All the artifacts have a negative Nb anomaly and some have enriched LREEs compared to the outcrop samples. See text for explanation.

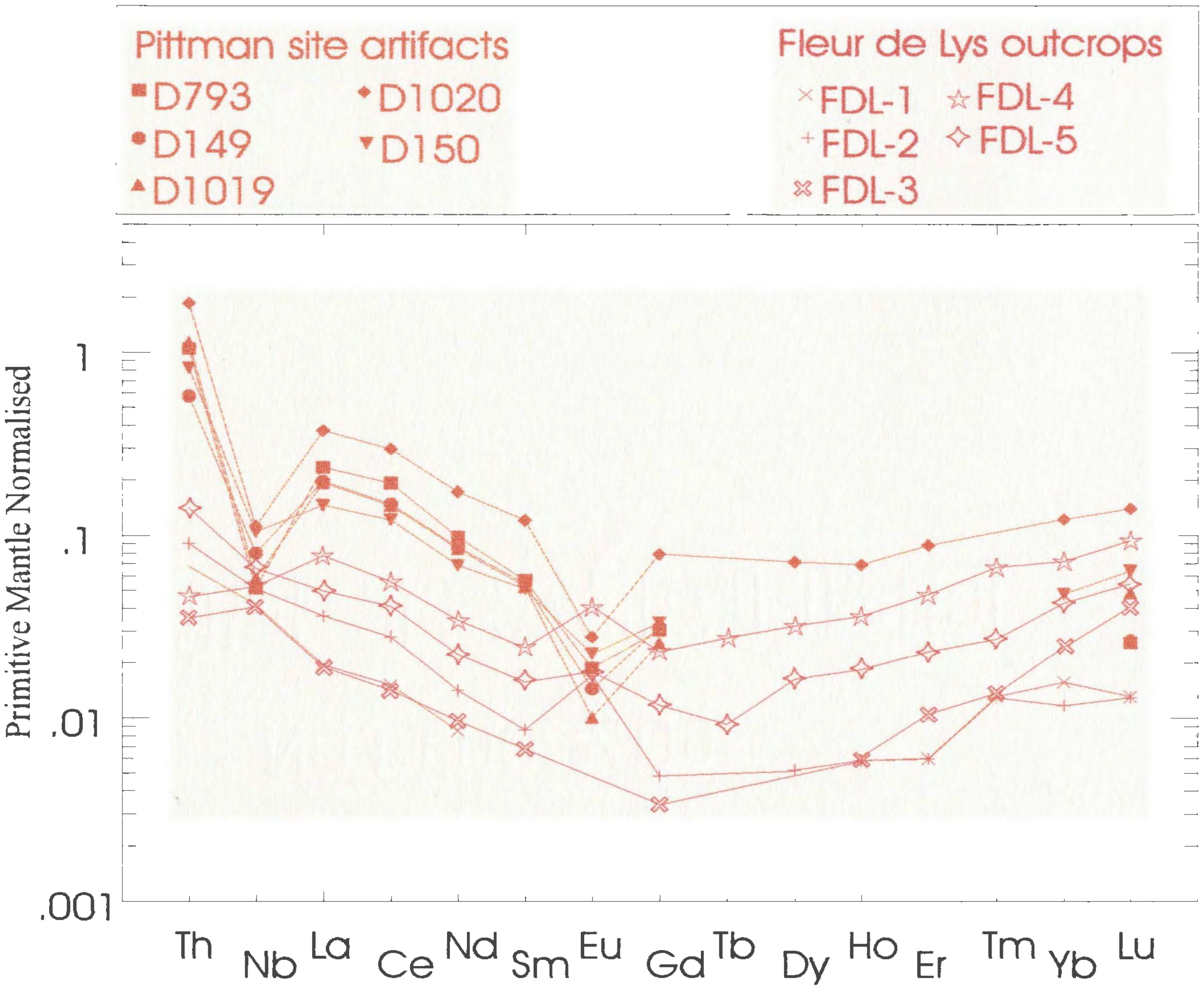


Figure 4.12: Primitive mantle normalised diagram of Pittman site artifacts versus Fleur de Lys outcrop samples.

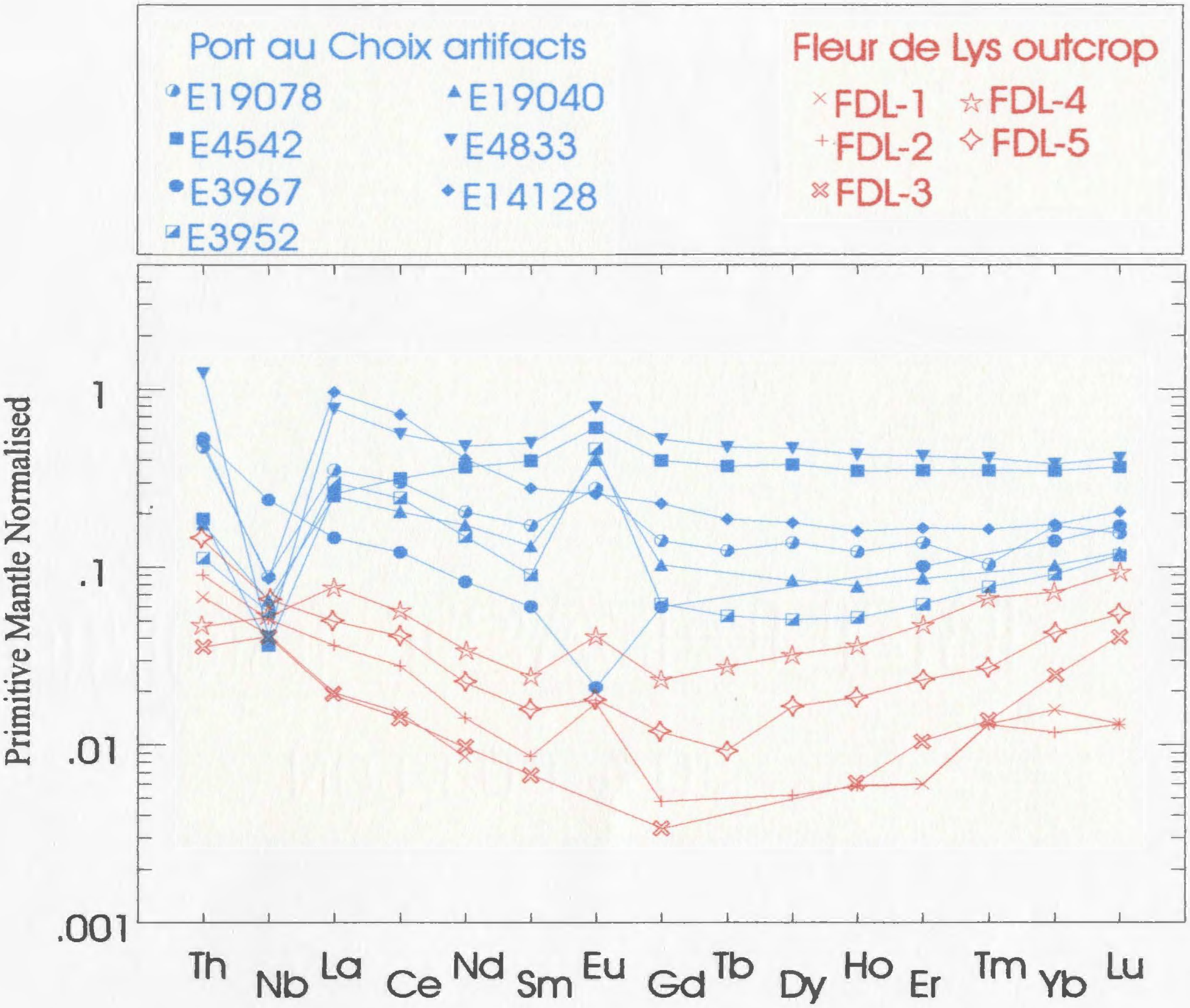


Figure 4.13: Primitive mantle normalised diagram of Port au Choix artifacts and Fleur de Lys outcrop samples. Artifacts have enriched REEs compared to Fleur de Lys and have a flat HREE pattern. These groups of patterns are so dissimilar that, clearly, Fleur de Lys is not thesource of the Dorset artifacts recovered from Port au Choix.

4.4.2.2 A Comparison of REE Patterns between Fleur de Lys Artifacts and Artifacts from Other Sites

The following discussion compares the REE patterns of the different artifact groups. The groups are compared to artifacts from the Fleur de Lys quarry because this is the only known prehistoric Dorset quarry in Newfoundland.

Englee artifacts and Fleur de Lys artifacts overlap on a PM-normalised REE diagram and have the same trend (Fig. 4.14). Patterns for both groups generally exhibit negative Nb anomalies. In detail, each artifact group has two types of REE patterns. One type is LREE enriched, with a steep positive sloped LREE trend and a flat HREE trend, the other pattern type is more U or V-shaped with a shallow positive sloped LREE trend and a shallow negative sloped HREE trend. The overlapping patterns suggest the Englee and Fleur de Lys artifacts are likely from the same Fleur de Lys quarry sources.

Fleur de Lys and Pittman site artifacts have similar LREE patterns (Fig. 4.15), with LREE concentrations of the Fleur de Lys artifacts bracketing those of the Pittman artifacts. Similarities between the two sites also include Th enrichment and a negative Nb anomaly. Due to the lack of much of the HREE data for most of the Pittman artifacts (except D1020), the entire trend must be inferred; however the Lu concentrations provide reasonable control of the slope direction.

When Port au Choix artifacts are compared to Fleur de Lys artifacts (Fig. 4.16), it is evident that the Port au Choix artifacts have much flatter REE patterns, especially for

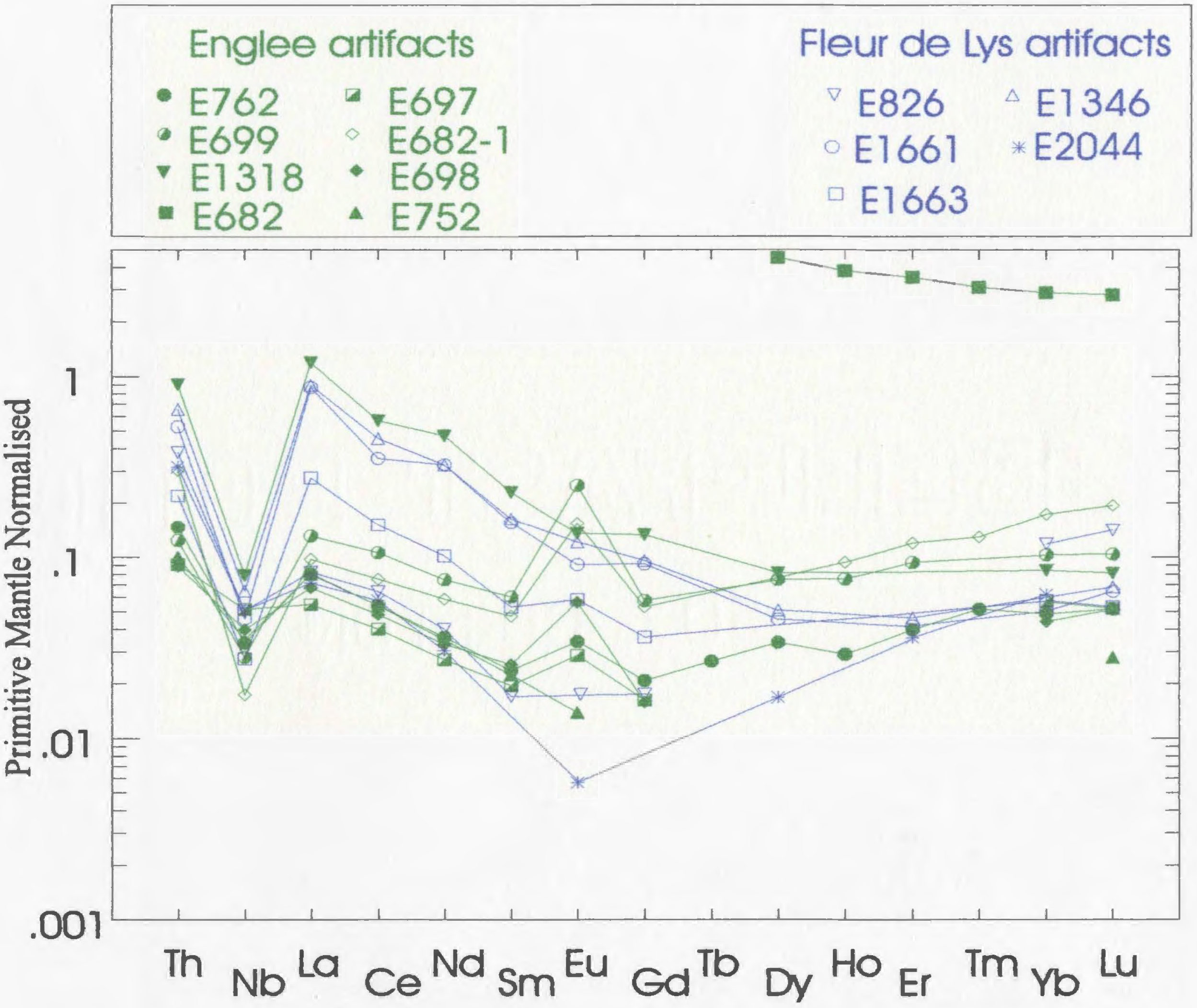


Figure 4.14: Primitive mantle normalised REE diagram comparing Englee artifacts to artifacts from Fleur de Lys. Other than Englee sample E682 which is considered not to be an artifact, the samples have similar REE patterns (especially LREEs). All artifacts have negative Nb anomaly and enriched La. These artifacts are likely from the same quarry at Fleur de Lys.

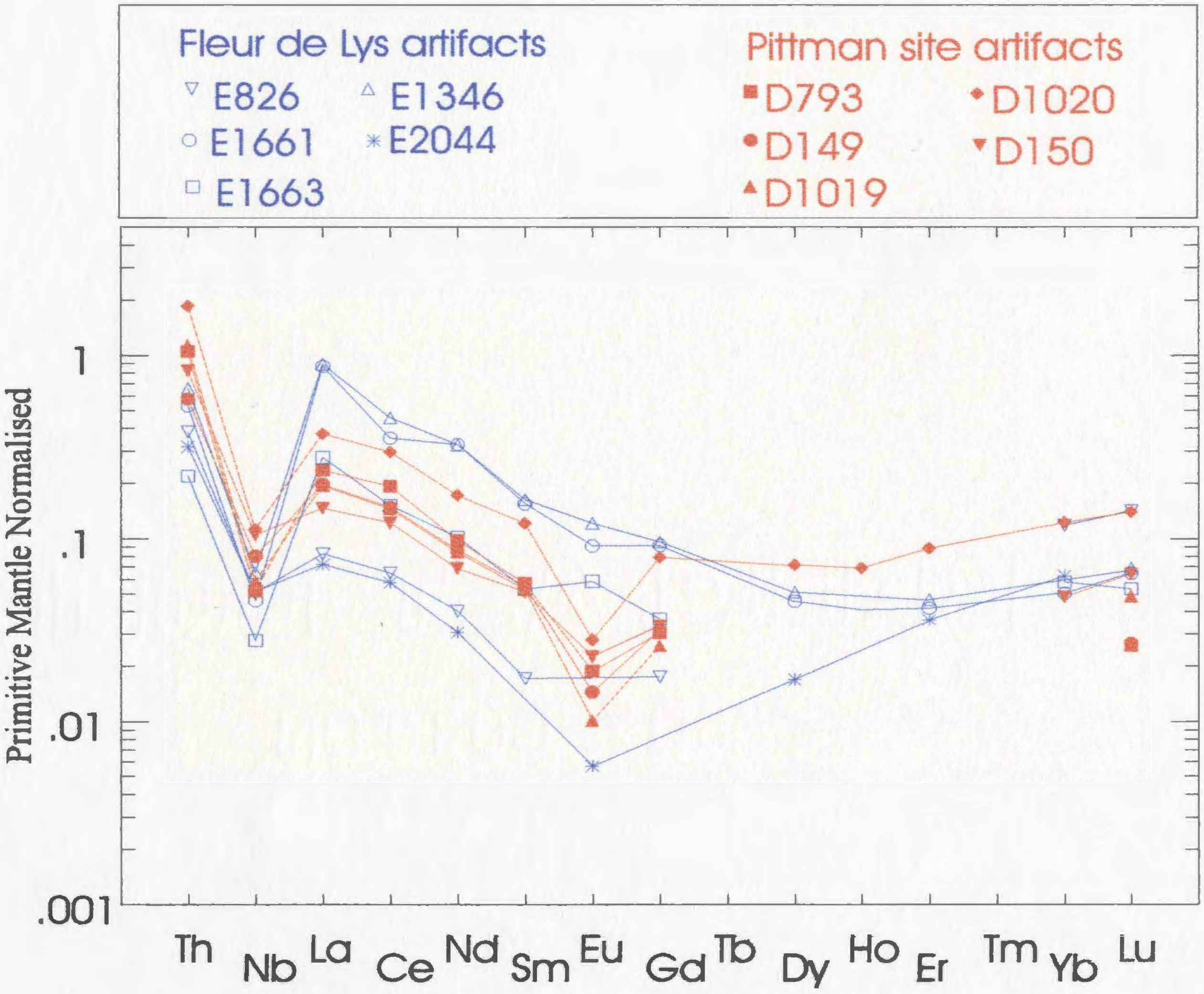


Figure 4.15: Primitive mantle normalised diagram of Fleur de Lys and Pittman site artifacts. Both sites have similar REE patterns although concentrations differ slightly (e.g. negative Nb anomaly; LREE enrichment).

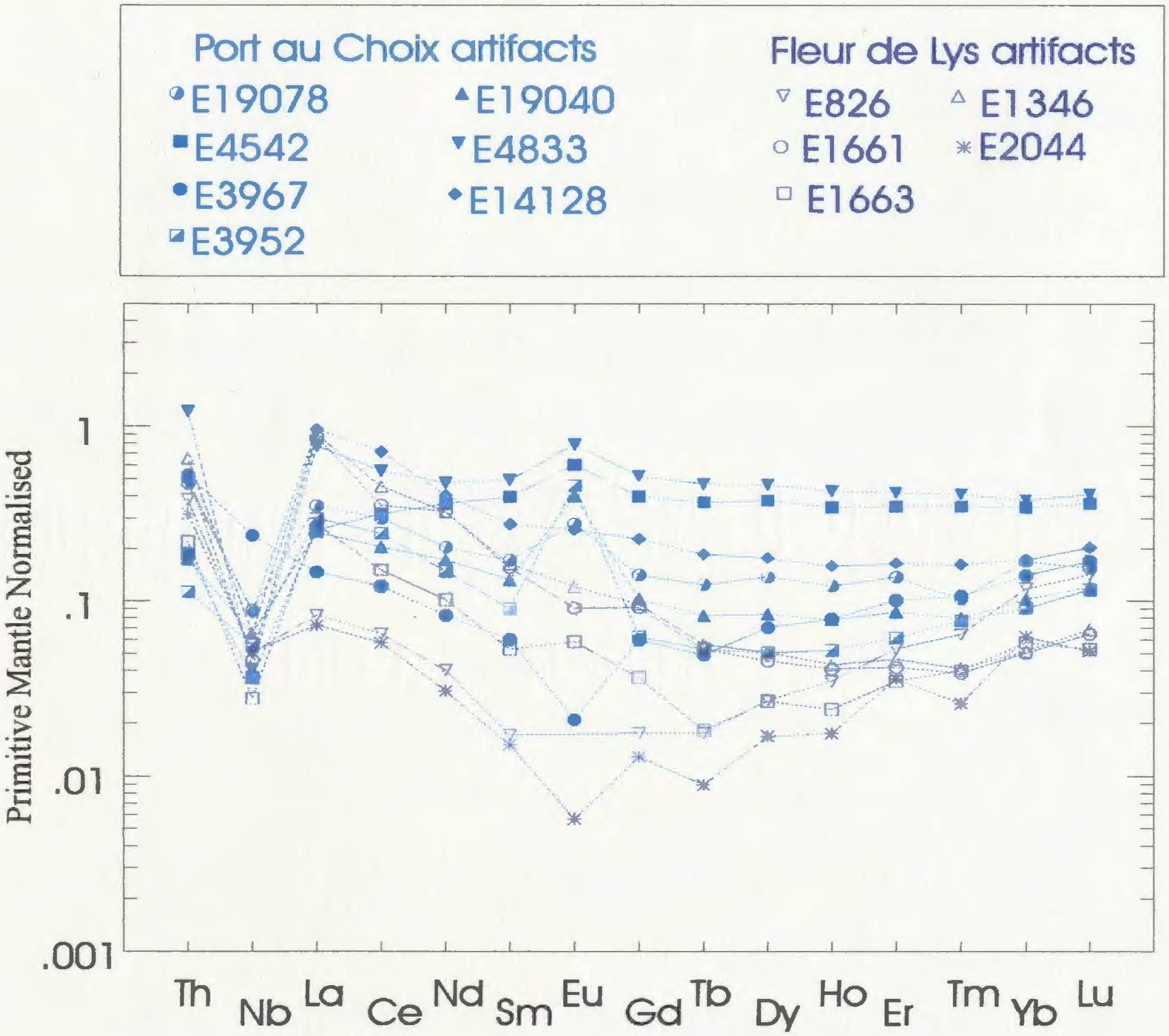


Figure 4.16: Primitive mantle normalised REE plot of Port au Choix versus Fleur de Lys artifacts. A negative Nb anomaly is characteristic of almost all samples, except E3967. Port au Choix samples have a flat HREE pattern, except for the Eu anomaly, and have higher concentrations of REEs in general than Fleur de Lys.

the HREEs, though both groups of artifacts have a negative Nb anomaly (one exception); the Port au Choix artifacts generally have significantly higher concentrations of HREEs, suggesting they are not similar to Fleur de Lys artifacts.

4.4.2.3 A Comparison of REE Patterns of Different Outcrops

The REE patterns for outcrops from different regions of western Newfoundland were compared to one another to identify diagnostic features. A sample was taken from the Straitsview outcrop on the advice of a local resident. REE concentrations of the Straitsview sample differs significantly from those of the Fleur de Lys outcrop samples (Fig. 4.17). The high REE abundances of Straitsview and positive sloped REE pattern means it is not a possible source of artifacts, and likely is not even an ultramafic rock (i.e., Straitsview is likely a basalt), thus is not relevant to the remainder of this study.

In a comparison of all ultramafic outcrop samples from western Newfoundland, it is possible to see that there are significant geochemical differences between different outcrop areas, illustrative of different mantle sources and alteration styles between outcrops. It is apparent that outcrop samples from St. Anthony exhibit a completely different and distinct REE pattern and that the other outcrop patterns mostly overlap with Fleur de Lys outcrop samples (Fig. 4.18). The concentrations of HREEs in the St. Anthony samples are more than an order of magnitude higher than other outcrop samples. The Trout River and Tablelands samples appear quite similar to one another, but are somewhat distinct from the Fleur de Lys samples based on their enrichment in Th and the presence of a weak negative Nb anomaly.

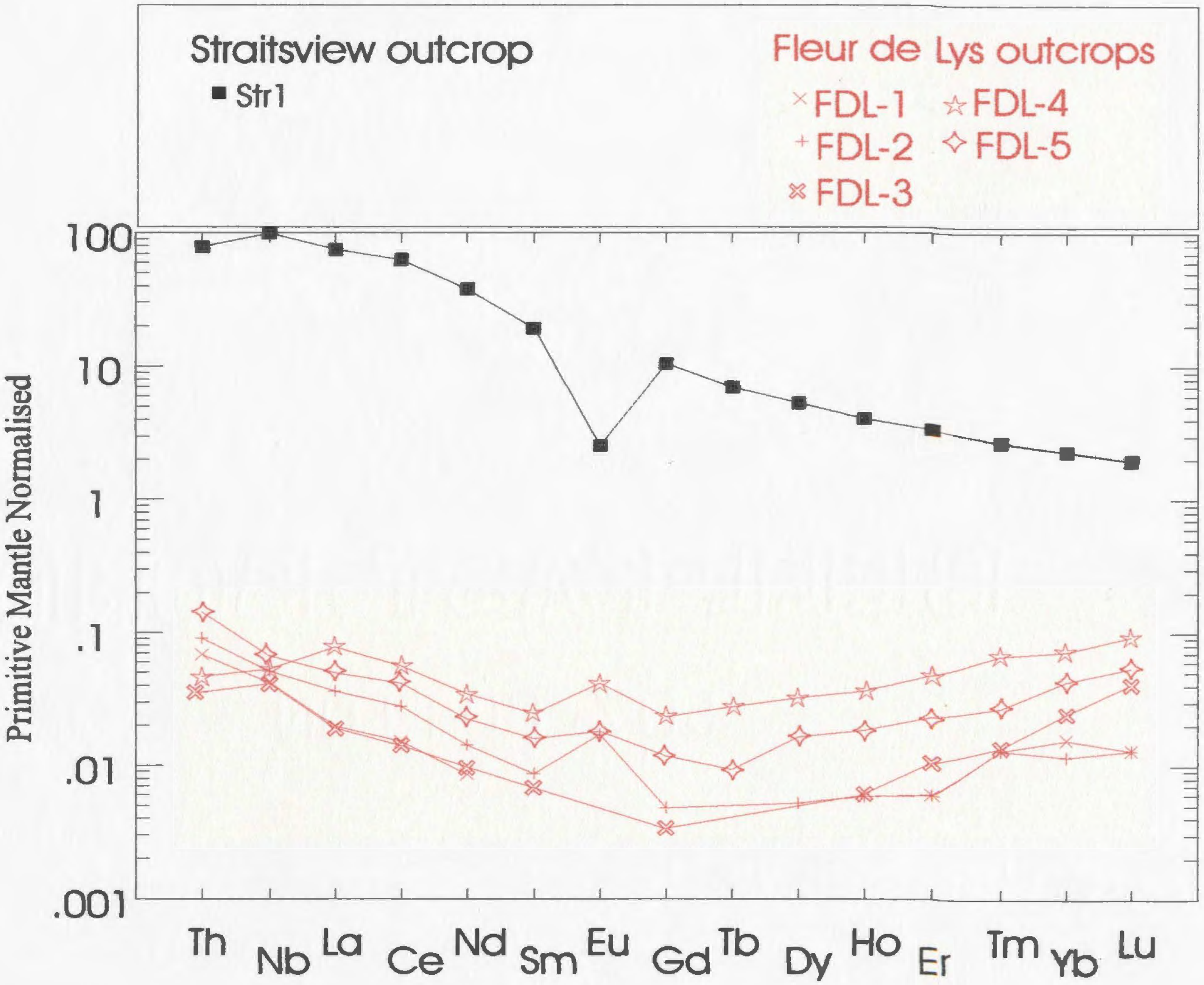


Figure 4.17: Primitive mantle normalised diagram illustrating compositions of Fleur de Lys and Straitsview outcrops. The Straitsview sample is basaltic in composition.

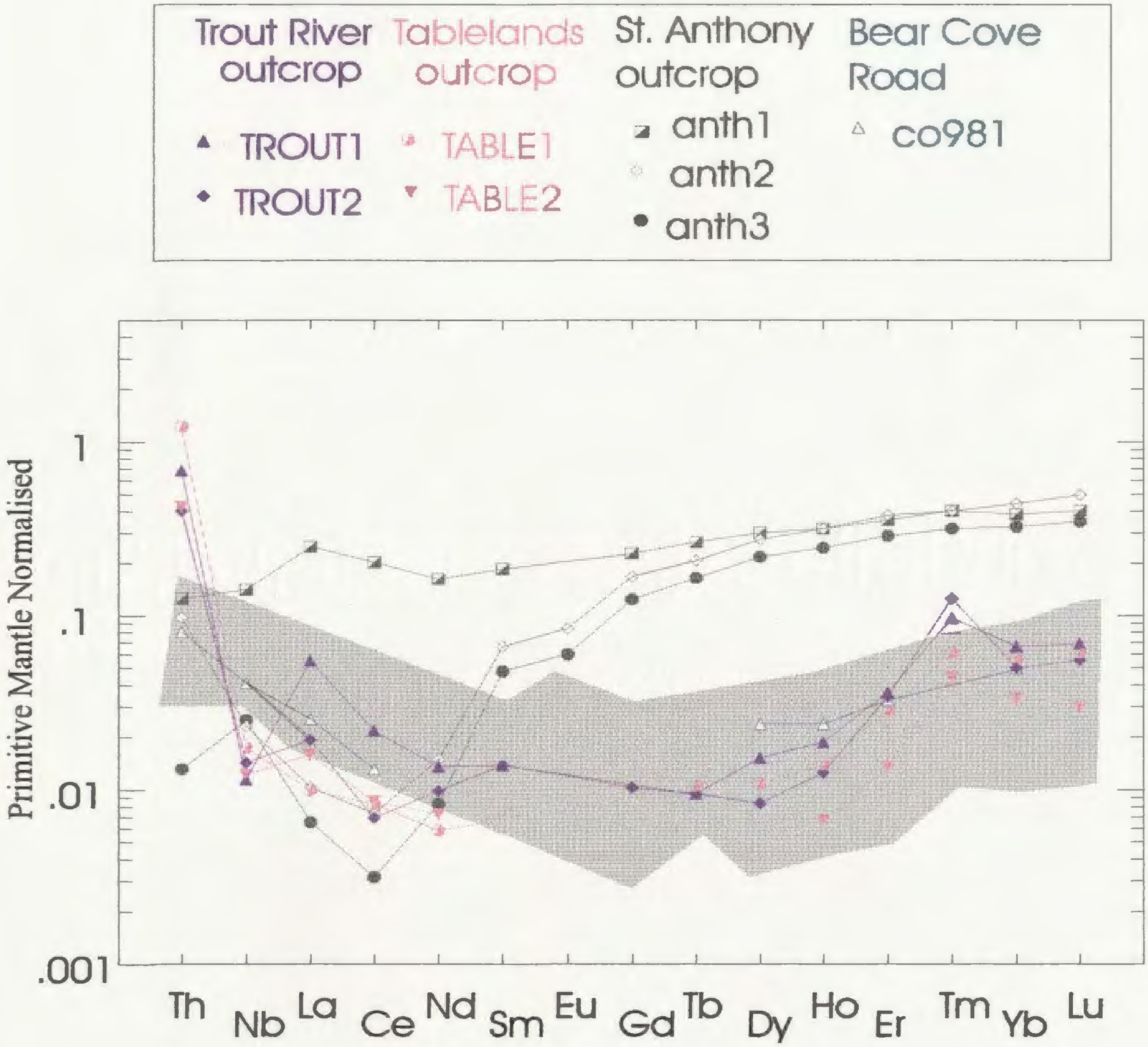


Figure 4.18: Primitive mantle normalised REE plot comparing all outcrop samples against Fleur de Lys outcrops which are represented by the grey shading. St. Anthony exhibits a completely different pattern than all other samples and HREEs cluster tightly and have concentrations more than an order of magnitude higher than the REEs in other outcrops. All samples other than St. Anthony mostly overlap.

The Bear Cove Road sample, collected on the Baie Verte Peninsula approximately 45 km south of the Fleur de Lys quarry, appears to have a very similar REE pattern to the quarry outcrop samples.

4.5 Summary of Results

In general, the geochemistry of the artifacts shows four main characteristics compared to the outcrop samples: 1) LREE enrichment; 2) Th enrichment; 3) most have negative Nb anomaly; and 4) typically higher LOI values.

There is a wide range of LOI values for both artifact and outcrop samples. For the artifacts, LOI values vary from 5 to 26% (mean 17%) which differs somewhat from the outcrop samples which LOI values vary from 5 to 21% (mean 12%). One notable exception is artifacts from Cape Ray which have LOI values of 4-9% which suggests these artifacts have lower per cent concentrations of magnesite.

Sample E682 from Englee is not ultramafic and is likely not a soapstone artifact. It is clearly distinguished from the rest of the Englee samples by an enriched REE pattern.

Within the outcrop samples are some general characteristics. St. Anthony outcrop samples are quite distinct from other outcrops and exhibit an enriched flat HREE pattern. The Trout River and Tablelands outcrop samples have a negative Nb anomaly, variation in LREE concentrations and HREE patterns overlap with Fleur de Lys HREE patterns, excepting a high concentration of Tm. The Straitsview outcrop contains concentrations of REEs many orders of magnitude above other samples tested. It is basaltic in composition and is unrelated to this study.

Table 4.1: Geochemical data for artifact samples. Lightly shaded areas represent artifact samples with no XRF data. Elements below the ICP-MS detection limit are represented by b.d. All major elements as well as Cr, Ni, Sc, and V are reported as volatile-free.

Site Location	Englee 2	Englee 3	Englee 2	Englee 1	Englee 3	Englee 3	Englee 3
Sample Name	E762	E682	E752	E1318	E698	E699	E697-REP
Artifact No.	EeBa-2:762	EeBa-3:682	EeBa-2:752	EeBa-1:1318	EeBa-3:698	EeBa-3:699	EeBa-3:697
Analysis # (Run)	ICP783	ICP788	ICP788	ICP788	ICP787	ICP787	ICP787
SiO_2 (wt%)	49.99		44.64	54.06	52.72	46.92	47.00
TiO_2	b.d.		b.d.	0.02	b.d.	b.d.	b.d.
Al_2O_3	0.58		11.66	0.62	0.41	0.29	0.47
Fe_2O_3	7.46		7.55	8.03	6.77	8.19	8.75
MnO	0.09		0.09	0.16	0.09	0.13	0.12
MgO	46.59		43.04	43.85	44.38	43.72	46.24
CaO	0.16		0.15	0.12	1.23	5.68	1.21
Na_2O	0.16		0.18	0.18	0.19	0.19	0.12
K_2O	b.d.		b.d.	b.d.	b.d.	b.d.	b.d.
P_2O_5	0.03		0.03	0.02	0.11	0.13	0.27
total	105.06		107.34	107.05	105.90	105.25	104.24
LOI	21.48	20.95	24.22	17.55	22.36	24.73	24.88
Cr (ppm)	3469		2558	2678	2617	2975	3045
Ni	2241		2124	2391	2146	2038	1953
Sc	16		12	6	10	11	14
V	34		29	13	12	36	28
Nb	0.025	11.472	0.027	0.060	0.030	0.021	0.038
Hf	0.012	1.194	0.022	0.110	0.021	0.027	0.030
Rb	0.074	13.755	b.d.	0.274	b.d .	b.d	b.d
Sr	2.881	76.435	2.16	2.994	99.715	309.066	63.915
Zr	0.419	34.538	0.535	1.907	0.512	0.710	0.728
Y	0.173	15.838	0.050	0.397	0.167	0.468	0.173
Th	0.013	6.787	0.009	0.081	0.008	0.011	0.008
Cs	0.040	0.303	b.d.	b.d.	b.d.	b.d	b.d
Ba	1.773	116.730	2.62	24.680	6.470	6.850	7.000
La	0.058	23.012	0.059	0.869	0.049	0.094	0.039
Ce	0.101	50.974	0.103	1.076	0.091	0.197	0.074
Pr	0.013	6.085	b.d	0.179	0.013	0.025	b.d
Nd	0.051	24.216	0.050	0.672	0.047	0.106	0.038
Sm	0.011	4.813	0.011	0.108	0.012	0.028	0.009
Eu	0.006	0.969	0.003	0.024	0.010	0.044	0.005
Gd	0.013	4.168	b.d.	0.084	0.010	0.036	0.010
Tb	0.003	0.577	b.d.	b.d.	b.d	b.d	b.d
Dy	0.026	3.310	b.d.	0.064	b.d	0.058	b.d
Ho	0.005	0.626	b.d.	b.d.	b.d	0.013	b.d
Er	0.020	1.692	b.d.	b.d.	b.d	0.047	b.d
Tm	0.004	0.228	b.d.	b.d.	b.d	b.d	b.d
Yb	0.025	1.425	b.d.	0.044	0.023	0.053	0.029
Lu	0.004	0.209	0.002	0.006	0.004	0.008	0.004

Table 4.1 (cont'd): Geochemical data for artifact samples. Lightly shaded areas represent artifact samples with no XRF data. Elements below the ICP-MS detection limit are represented by b.d. All major elements as well as Cr, Ni, Sc, and V are reported as volatile-free.

Site Location	Englee 3	Fleur de Lys	Fleur de Lys	Fleur de Lys	Fleur de Lys	Fleur de Lys	Port au Choix
Sample Name	E682-1	E826	E1346	E1661	E1663	E2044	E3967
Artifact No.	EeBa-3:682-1	EaBa-1:826	EaBa-1: 1346	EaBa-1: 1661	EaBa-1: 1663	EaBa-1:2044	EeBi-1:3967
Analysis # (Run)	ICP787	ICP788	ICP787	ICP787	ICP787	ICP782	ICP788
SiO2 (wt%)	49.96	55.29	48.46	53.03	47.70	51.85	48.48
TiO2	b.d.	b.d.	0.04	b.d.	0.01	b.d.	0.01
Al2O3	0.21	1.05	0.30	0.49	0.31	0.52	0.24
Fe2O3	8.09	6.19	8.09	9.12	8.34	7.41	6.77
MnO	0.16	0.07	0.13	0.09	0.17	0.05	0.15
MgO	43.61	42.93	41.94	42.46	45.21	44.90	49.38
CaO	2.84	0.08	0.10	0.07	0.42	0.14	0.26
Na2O	0.19	0.17	0.16	0.18	0.19	0.16	0.23
K2O	b.d.	b.d.	0.01	b.d.	b.d.	b.d.	b.d.
P2O5	0.14	0.05	0.03	0.02	0.07	0.02	0.10
total	105.23	105.84	99.26	105.49	102.46	105.05	105.66
LOI	20.95	12.04	18.62	16.20	22.71	18.85	25.92
Cr (ppm)	1992	3269	2762	3410	2438	3400	1987
Ni	2256	2029	2216	2698	2169	2348	2815
Sc	6	1	1	6	9	6	5
V	18	33	23	47	21	35	16
Nb	0.013	0.041	0.046	0.034	0.020	0.038	0.178
Hf	0.119	0.129	0.116	0.113	0.042	0.041	0.036
Rb	b.d	0.142	b.d	b.d	b.d	0.148	0.077
Sr	163.581	2.959	2.878	2.303	13.738	1.172	3.140
Zr	2.227	1.782	1.555	1.791	0.941	1.303	0.572
Y	0.562	0.204	0.228	0.216	0.190	0.146	0.446
Th	0.027	0.019	0.055	0.047	0.019	0.028	0.047
Cs	b.d	b.d	b.d	b.d	b.d	0.039	b.d
Ba	12.510	12.930	20.490	11.520	21.880	5.823	7.460
La	0.070	0.063	0.602	0.624	0.193	0.052	0.105
Ce	0.141	0.121	0.796	0.656	0.273	0.107	0.226
Pr	0.018	b.d	0.120	0.126	0.038	0.010	0.028
Nd	0.083	0.065	0.432	0.460	0.139	0.043	0.117
Sm	0.022	0.013	0.071	0.072	0.024	b.d	0.028
Eu	0.027	0.003	0.020	0.016	0.010	0.001	0.004
Gd	0.033	0.015	0.056	0.057	0.022	b.d	0.037
Tb	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Dy	0.059	b.d	0.037	0.035	b.d	0.013	b.d
Ho	0.016	b.d	b.d	b.d	b.d	b.d	b.d
Er	0.060	b.d	0.022	0.021	b.d	0.018	0.051
Tm	0.010	b.d	b.d	b.d	b.d	b.d	b.d
Yb	0.089	0.066	b.d	0.026	0.029	0.032	0.073
Lu	0.015	0.016	0.005	0.005	0.004	b.d	b.d.

Table 4.1 (cont'd): Geochemical data for artifact samples. Lightly shaded areas represent artifact samples with no XRF data. Elements below the ICP-MS detection limit are represented by b.d. All major elements as well as Cr, Ni, Sc, and V are reported as volatile-free.

Site Location	Port au Choix	Port au Choix	Port au Choix	Port au Choix	Port au Choix	Port au Choix	Cape Ray
Sample Name	E4542	E19040	E4833	E14128	E19078	E3952	C2801
Artifact No.	EeBi-1:4542	EeBi-1:19040	EeBi-1:4833	EeBi-1:14128	EeBi-1:19078	EeBi-1:3952	CjBt-1:2801
Analysis # (Run)	ICP787	ICP787	ICP787	ICP787	ICP782	ICP783	ICP787
SiO2 (wt%)	47.63	41.59	45.20	46.39	46.88	46.40	58.50
TiO2	0.07	0.05	0.10	0.04	0.04	0.03	0.08
Al2O3	6.03	7.26	3.09	3.57	2.41	4.84	1.77
Fe2O3	9.88	10.08	11.06	9.43	11.73	12.58	8.81
MnO	0.12	0.11	0.18	0.23	0.20	0.15	0.03
MgO	33.72	37.38	35.68	36.28	40.53	36.52	37.05
CaO	3.97	5.72	8.28	4.28	4.20	4.94	0.02
Na2O	0.16	0.19	0.15	0.15	0.13	0.14	0.18
K2O	b.d.	0.01	b.d.	b.d.	0.01	0.01	0.04
P2O5	0.02	0.03	0.16	0.20	0.04	0.42	0.01
total	101.62	102.43	103.93	100.60	106.17	106.03	106.50
LOI	11.81	13.89	17.50	11.96	22.08	12.52	5.33
Cr (ppm)	1408	430	1480	1596	2165	588	1824
Ni	1122	1060	1060	1202	1710	1025	1091
Sc	17	7	11	15	12	5	8
V	40	13	57	21	35	16	79
Nb	0.026	0.047	0.030	0.061	0.066	0.042	0.230
Hf	0.130	0.039	0.071	0.176	0.018	0.007	0.040
Rb	0.573	0.586	b.d	b.d	0.106	0.204	0.876
Sr	18.585	46.445	60.261	20.043	23.685	59.451	4.678
Zr	2.315	0.552	1.270	2.579	0.393	0.244	0.989
Y	1.362	0.374	1.762	0.713	0.614	0.243	0.098
Th	0.016	0.015	0.107	0.042	0.042	0.010	0.241
Cs	0.242	0.352	0.273	b.d	0.100	0.121	b.d
Ba	3.910	2.840	4.500	25.720	1.344	38.463	21.020
La	0.177	0.174	0.546	0.654	0.254	0.214	0.184
Ce	0.565	0.369	1.019	1.268	0.557	0.455	0.352
Pr	0.095	0.052	0.137	0.131	0.063	0.052	0.040
Nd	0.492	0.236	0.663	0.542	0.288	0.210	0.143
Sm	0.177	0.059	0.226	0.122	0.080	0.042	0.026
Eu	0.102	0.068	0.136	0.043	0.049	0.081	0.005
Gd	0.239	0.062	0.319	0.135	0.088	0.039	0.020
Tb	0.040	b.d	0.052	0.020	0.014	0.006	b.d
Dy	0.280	0.063	0.351	0.130	0.106	0.039	b.d
Ho	0.057	0.013	0.072	0.026	0.021	0.009	b.d
Er	0.169	0.042	0.207	0.079	0.069	0.031	b.d
Tm	0.026	b.d	0.031	0.012	0.008	0.006	b.d
Yb	0.172	0.051	0.192	0.085	0.088	0.047	0.012
Lu	0.027	0.009	0.031	0.015	0.012	0.009	0.002

Table 4.1 (cont'd): Geochemical data for artifact samples. Lightly shaded areas represent artifact samples with no XRF data. Elements below the ICP-MS detection limit are represented by b.d. All major elements as well as Cr, Ni, Sc, and V are reported as volatile-free.

Site Location	Cape Ray	Cape Ray	Cape Ray	Cape Ray	Cape Ray	Pittman site	Pittman site
Sample Name	C2824	C2898	C3121	C2896	C2897	D149	D793
Artifact No.	CjBt-1:2824	CjBt-1:2898	CjBt-1:3121	CjBt-1:2896	CjBt-1:2897	DkBe-1:149	DkBe-1:793
Analysis # (Run)	ICP	ICP	ICP	ICP	ICP	ICP	ICP
SiO2 (wt%)		58.90	52.19	48.45	44.99	53.23	47.78
TiO2		0.06	0.03	0.11	0.06	b.d.	b.d.
Al2O3		1.21	4.31	4.28	8.55	0.29	0.25
Fe2O3		9.26	10.20	11.89	11.37	7.82	9.08
MnO		0.03	0.04	0.07	0.03	0.08	0.17
MgO		38.20	36.47	33.40	36.11	45.95	46.97
CaO		0.01	0.47	0.02	0.02	0.12	0.24
Na2O		0.15	0.18	0.14	0.19	0.19	0.21
K2O		b.d.	0.02	0.02	0.02	b.d.	0.02
P2O5		b.d.	0.04	0.21	0.04	0.12	0.51
total		107.85	103.97	98.59	101.40	107.83	105.26
LOI	5.15	6.08	8.16	7.90	9.36	23.48	25.67
Cr (ppm)		4262	1820	1844	678	2806	1720
Ni		1317	1604	1427	1043	1905	2149
Sc		8	10	8	8	9	2
V		69	20	73	53	26	20
Nb	0.665	0.179	0.156	0.943	0.080	0.061	0.039
Hf	0.054	0.131	0.069	0.039	0.150	0.041	0.035
Rb	0.133	0.214	0.776	0.476	0.509	0.125	0.152
Sr	2.059	1.124	10.074	3.962	3.661	4.039	20.888
Zr	1.034	2.196	1.660	0.898	2.749	0.908	0.860
Y	0.147	0.042	0.157	0.520	0.366	0.105	0.087
Th	0.249	0.110	0.148	0.286	0.102	0.052	0.093
Cs	0.038	0.019	0.242	0.210	0.132	b.d	b.d
Ba	4.100	2.650	27.250	11.945	11.110	14.990	30.480
La	0.342	0.203	0.317	0.702	0.325	0.145	0.169
Ce	0.847	0.397	0.680	1.905	0.577	0.283	0.359
Pr	0.074	0.041	0.073	0.205	0.064	0.033	0.037
Nd	0.284	0.142	0.272	0.811	0.260	0.125	0.138
Sm	0.054	0.023	0.048	0.183	0.063	0.026	0.026
Eu	0.007	0.004	0.052	0.047	0.020	0.003	0.003
Gd	0.040	0.014	0.032	0.149	0.067	0.020	0.019
Tb	b.d	b.d	b.d	0.023	b.d	b.d	b.d
Dy	b.d	b.d	b.d	0.146	0.061	b.d	b.d
Ho	b.d	b.d	b.d	0.025	0.012	b.d	b.d
Er	b.d	b.d	b.d	0.074	0.037	b.d	b.d
Tm	b.d	b.d	b.d	0.009	b.d	b.d	b.d
Yb	b.d	b.d	b.d	0.076	0.038	b.d	b.d
Lu	0.003	0.002	0.003	0.009	0.006	0.002	0.002

Table 4.1 (cont'd): Geochemical data for artifact samples. Lightly shaded areas represent artifact samples with no XRF data. Elements below the ICP-MS detection limit are represented by b.d. All major elements as well as Cr, Ni, Sc, and V are reported as volatile-free.

Site Location	Pittman site	Pittman site	Pittman site
Artifact No.	DkBe-1:1019	DkBe-1:150	DkBe-1:1020
Sample Name	D1019	D150	D1020
Analysis # (Run)	ICP788	ICP788	ICP787
SiO2 (wt%)	50.59	55.54	53.62
TiO2	b.d.	b.d.	0.00
Al2O3	0.21	0.39	0.60
Fe2O3	7.62	6.54	7.88
MnO	0.10	0.06	0.07
MgO	47.88	43.25	43.49
CaO	0.11	0.08	0.14
Na2O	0.23	0.17	0.22
K2O	b.d.	0.01	0.03
P2O5	0.11	0.18	0.98
total	106.88	106.25	107.07
LOI	22.16	16.16	17.04
Cr (ppm)	3387	3016	4160
Ni	2061	2274	1830
Sc	12	5	3
V	25	31	45
Nb	0.044	0.080	0.085
Hf	0.028	0.052	0.025
Rb	0.118	0.279	b.d
Sr	4.357	2.458	21.328
Zr	0.570	1.246	0.503
Y	0.071	0.125	0.313
Th	0.102	0.073	0.167
Cs	0.038	0.062	b.d
Ba	8.060	6.920	62.470
La	0.142	0.096	0.272
Ce	0.274	0.203	0.559
Pr	0.034	0.024	0.068
Nd	0.121	0.092	0.248
Sm	0.025	0.021	0.057
Eu	0.002	0.002	0.005
Gd	0.016	0.021	0.050
Tb	b.d	b.d	b.d
Dy	b.d	b.d	0.056
Ho	b.d	b.d	0.012
Er	b.d	b.d	0.045
Tm	b.d	b.d	b.d
Yb	b.d	0.025	0.064
Lu	0.004	0.004	0.011

Table 4.2: Geochemical data for outcrop samples. Element concentrations below the ICP-MS detection limit are represented by b.d. All major elements as well as Cr, Ni, Sc, and V are reported as volatile-free.

Site Location	Howe Harbour	Howe Harbour	Howe Harbour	Bear Cove Road	Fleur de Lys	Fleur de Lys	Fleur de Lys
Sample Name	anth1	anth3	anth2	co981	FDL-1	FDL-2	FDL-3
Analysis # (Run)	ICP773	ICP783	ICP787	ICP773	ICP783	ICP783	ICP783
SiO2 (wt%)	38.82	35.02	33.87	41.04	44.17	52.01	42.55
TiO2	0.05	0.02	0.02	b.d.	b.d.	b.d.	b.d.
Al2O3	1.67	1.10	1.13	0.34	0.31	0.28	0.42
Fe2O3	9.36	10.06	10.08	8.14	7.40	8.25	6.70
MnO	0.14	0.14	0.14	0.21	0.09	0.08	0.09
MgO	43.48	41.93	38.30	52.68	52.28	44.36	50.04
CaO	1.26	1.98	2.05	0.85	0.02	0.11	0.05
Na2O	0.21	0.19	0.19	0.19	0.20	0.14	0.17
K2O	0.02	0.01	b.d.	b.d.	b.d.	b.d.	b.d.
P2O5	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
total	**95.01**	**90.45**	**85.79**	**103.45**	**104.47**	**105.23**	**100.02**
LOI	9.01	6.13	5.06	12.75	14.24	21.26	12.14
Cr (ppm)	3562	3012	3158	3192	3578	3626	3603
Ni	2479	2234	2057	2450	2563	2849	2479
Sc	1	1	7	1	1	3	7
V	66	61	66	37	31	29	34
Nb	0.095	0.008	0.014	0.030	0.014	0.038	0.029
Hf	0.054	0.014	0.046	0.044	0.002	0.028	0.004
Rb	0.529	0.117	b.d	b.d.	b.d	0.105	b.d
Sr	10.730	7.640	4.490	8.290	1.520	2.450	1.900
Zr	0.668	0.170	0.625	0.549	0.112	0.347	0.111
Y	1.238	0.925	1.215	0.132	0.017	0.029	0.032
Th	0.010	0.001	0.007	0.007	0.002	0.008	0.003
Cs	0.301	0.057	b.d	b.d	b.d	0.048	b.d
Ba	6.130	5.160	2.940	0.670	1.050	0.880	0.100
La	0.161	0.010	b.d.	0.020	0.016	0.026	0.013
Ce	0.341	0.005	0.011	0.024	0.019	0.052	0.025
Pr	0.052	0.007	b.d.	b.d	0.008	0.006	0.004
Nd	0.207	0.015	0.017	b.d	0.013	0.020	0.013
Sm	0.078	0.022	0.025	b.d	b.d	0.004	0.003
Eu	b.d.	0.008	0.012	b.d	b.d	0.003	b.d
Gd	0.128	0.066	0.085	b.d	b.d	0.003	0.002
Tb	0.027	0.017	0.019	b.d	b.d	b.d	b.d
Dy	0.208	0.148	0.172	0.018	b.d	0.004	b.d
Ho	0.049	0.038	0.044	0.004	0.001	0.001	0.001
Er	0.160	0.130	0.153	0.016	0.003	0.003	0.005
Tm	0.028	0.024	0.025	b.d	0.003	0.001	0.001
Yb	0.178	0.152	0.184	0.025	0.006	0.006	0.012
Lu	0.028	0.024	0.031	b.d	0.001	0.001	0.003

Table 4.2 (cont'd): Geochemical data for outcrop samples. Element concentrations below the ICP-MS detection limit are represented by b.d. All major elements as well as Cr, Ni, Sc, and V are reported as volatile-free.

Site Location	Fleur de Lys	Fleur de Lys	Trout River	Trout River	Tablelands	Tablelands	Straitsview
Sample	FDL-4	FDL-5	TROUT1	TROUT2	TABLE2	TABLE1	STR1
Analysis # (Run)	ICP783	ICP783	ICP838	ICP838	ICP838	ICP838	ICP782
SiO2 (wt%)	44.79	42.39	40.35	38.41	36.43	35.24	29.24
TiO2	b.d.	b.d.	0.01	b.d.	b.d.	b.d.	2.11
Al2O3	0.31	0.43	0.50	0.33	0.30	0.43	14.78
Fe2O3	8.83	8.10	10.80	10.29	9.91	10.06	19.51
MnO	0.12	0.13	0.16	0.14	0.14	0.14	0.58
MgO	47.80	49.05	46.40	49.01	45.17	42.61	33.30
CaO	0.07	0.14	0.95	0.61	0.66	0.84	0.80
Na2O	0.17	0.17	0.16	0.18	0.17	0.18	0.14
K2O	0.01	b.d.	b.d.	b.d.	b.d.	b.d.	0.01
P2O5	b.d.	0.01	b.d.	b.d.	b.d.	b.d.	0.41
total	**102.10**	**100.42**	**99.33**	**98.97**	**92.78**	**89.53**	**100.88**
LOI	15.04	14.58	10.16	10.98	13.22	10.96	9.98
Cr (ppm)	2627	3201	3420	2981	2624	2989	18
Ni	3188	2666	2393	2588	2529	2431	6
Sc	10	4	11	7	8	11	12
V	34	26	50	39	34	44	222
Nb	0.038	0.047	0.010	0.018	0.030	0.014	70.037
Hf	0.004	0.034	0.043	0.021	0.131	0.046	1.042
Rb	0.354	0.104	0.063	0.040	0.103	0.069	0.102
Sr	1.570	2.060	1.540	0.720	0.870	0.850	9.100
Zr	0.115	0.373	1.054	b.d.	b.d.	0.834	35.434
Y	0.224	0.109	0.078	0.063	0.027	0.052	10.813
Th	0.004	0.012	0.016	0.010	0.014	0.008	6.638
Cs	0.313	0.033	0.008	0.007	0.032	b.d	0.168
Ba	1.400	5.910	0.410	0.300	0.430	0.750	3.560
La	0.054	0.034	0.005	0.005	0.007	0.006	50.945
Ce	0.101	0.073	0.009	0.009	0.015	0.011	110.874
Pr	0.012	0.008	0.001	0.001	0.001	b.d.	12.514
Nd	0.047	0.030	0.006	0.005	0.009	0.006	50.473
Sm	0.011	0.007	0.001	0.001	b.d.	b.d.	8.444
Eu	0.007	0.003	b.d.	b.d.	b.d.	b.d.	0.420
Gd	0.014	0.007	b.d.	0.006	b.d.	b.d.	6.173
Tb	0.003	0.001	0.001	0.001	b.d.	0.001	0.744
Dy	0.024	0.012	0.006	0.004	b.d.	0.002	3.875
Ho	0.006	0.003	0.002	0.001	0.001	0.001	0.656
Er	0.023	0.011	0.013	0.009	0.004	0.008	1.599
Tm	0.005	0.002	0.003	0.002	0.001	0.002	0.197
Yb	0.036	0.021	0.031	0.024	0.013	0.023	1.120
Lu	0.007	0.004	0.006	0.005	0.004	0.005	0.144

CHAPTER FIVE

DISCUSSION OF FINDINGS AND CONCLUSION

5.1 Introduction

A number of themes will be discussed in this chapter, including a review of the significance of the geochemical differences between the Fleur de Lys outcrops versus the Fleur de Lys artifacts, a review of the main petrographic and geochemical features of the artifact and outcrop samples, and an identification of sub-populations within the artifact groups. Then an investigation of which Dorset groups may have used the Fleur de Lys quarry is presented, a review of possible sources of soapstone other than the Fleur de Lys, and links between the geochemically defined sub-populations and Robbins' regional variants theory. The possible trade/exchange scenarios of Dorset soapstone are investigated and the ICP-MS data from this study is compared with INAA data from previous geoarchaeological studies of soapstone. This is followed by the conceptual and practical challenges encountered during this project, recommendations for future work based on the results and challenges of this study, and a statement of the main conclusions.

5.2 Discussion of Fleur de Lys Artifact and Outcrop Samples

The Fleur de Lys artifact samples and outcrop samples do not exhibit the same trace element and rare earth element (REE) patterns (Fig. 4.11) and, in thin section, there is more serpentine in samples of Fleur de Lys outcrops than in the artifacts, and more talc in the artifacts than in the outcrops. In particular, the artifacts appear significantly enriched in Th and the LREE compared to the outcrop samples. Because the outcrop samples were collected only a few metres from the quarry face, it was anticipated that their geochemical signatures would be very similar. The pronounced differences likely reflect the heterogeneous compositions of the outcrop due to the dynamic geological environment of the Fleur de Lys area and the precise manner in which the fluids infiltrated the rocks during metamorphism, serpentinisation, and carbonatisation. The fluids changed the mineralogy of the rocks and their chemical composition, but very localised flow through parts of the outcrop area, and not as much flow through other parts, would have resulted in a geochemically heterogeneous outcrop. This accounts for the varying degrees of alteration observed along the outcrop (i.e., geochemical and mineralogical differences between Fleur de Lys artifacts and outcrop samples). In attempting to characterise the samples with a geochemical "fingerprint", supposedly immobile trace elements were used in order to strip away the effects of variable degrees of alteration intensity. However, studies of other carbonate-rich alteration systems associated with mineral deposits (e.g., gold deposits) have shown that, in intensely altered rocks, the CO_2-rich fluids have produced pronounced enrichments in Th and the LREE (i.e., they are not immobile), and therefore the REE patterns for the same rock type become variable depending on intensity of alteration (Lentz 1996: 392; Ludden et al. 1982). In the case of Fleur de Lys, the artifacts are more carbonate-rich (i.e., more altered), and as Th and LREE become enriched, a characteristic negative Nb anomaly develops in the REE pattern because Nb is the most immobile of all the elements (i.e., Nb does not change appreciably from the outcrop signature). Likewise, the HREE are more immobile relative to Th and the LREE, and so differences between outcrop samples and the more intensely altered artifacts for elements such as Yb or Lu are much less pronounced.

The Dorset would have selected the softest and most malleable soapstone, which is evidenced by the failed attempts at quarrying on the Fleur de Lys Locality One quarry face. The softest soapstone would be the most carbonate-rich, the most altered part of the outcrop. The Fleur de Lys outcrop samples selected for this study were collected from areas not quarried by the Dorset, particularly along the ridge above the quarry face. This outcrop was not as strongly altered (i.e., was harder, therefore not a target for the Dorset), and therefore the outcrop samples collected were not representative (geochemically) of the quarry face from which the artifacts are made. The outcrop sampling procedure, though not ideal, was undertaken due to permit restrictions by the Provincial Archaeology Office in 1998, that restricted damaging the quarry face. Therefore, for discussion purposes, the Fleur de Lys artifact REE patterns are considered to be representative of those from the Fleur de Lys quarry, not the Fleur de Lys outcrop samples. These artifacts were recovered from the areas around Localities One and Two in the town of Fleur de Lys and are assumed to have been quarried from the nearby outcrop localities. Their REE patterns are compared to artifacts from other archaeological sites in western Newfoundland.

5.3 A Summary of the Main Petrological and Geochemical Characteristics of the Artifacts and Outcrops

The chemical composition of a metamorphic rock is controlled by the composition of the igneous protolith (i.e., parent), and the nature of the alteration process. Elements become mobile when fluids are introduced through alteration processes such as metamorphism, serpentinisation, and carbonatisation, which produce changes in the mineralogy and geochemistry of the parent rock. The elements that become mobile during these processes are regulated by the composition of the fluid phase, temperature, and the ratio of fluid to the host rock (Rollinson 1993:7). This alters the primary igneous mineral assemblage (e.g., olivine) to secondary minerals (e.g., serpentine, talc). The source of alteration can be determined by plotting elements such as Ba, Sr, and LOI against an index of alteration intensity, where a correlation equals mobility (Pearce 1996: 83). In this study, Ba, Sr, and LOI could not be used consistently as an alteration index. It was determined, however, that the source of alteration is not from granites or metasediments in the area, which would have supplied K and Rb, but likely from rocks with oceanic sources, due to the low K and Rb values in the samples tested.

The complete lack of primary igneous texture or mineralogy of these ultramafic rocks, as observed in thin section, combined with the low abundances of the REEs, present challenges "fingerprinting" ultramafic rocks (see Kerrich and Wyman 1996). Anomalous REE patterns are produced where alteration has caused REE mobility in shear zones and in terranes where water-rock ratios are high, coupled with the presence of CO_2 (i.e., carbonatisation). However, different igneous parent lithologies can also have different geochemical compositions due to differences in their primary sources, independent of any alteration effects. The increase in abundance of Th and the LREE are due to their incompatible igneous behaviour during element fractionation in magmas (e.g., see Buttler and Moffat 1986:111). The outcrop samples collected from the Bear Cove Road (Baie Verte Peninsula), Fleur de Lys, St. Anthony, Straitsview, Trout River, and Tablelands come from a wide geographic area so it might be expected that the different outcrops have different primary igneous (parent) compositions. The Bear Cove Road sample appears to have a very similar REE patterns to the Fleur de Lys quarry outcrop samples which is not unexpected because both rock units occur along the same structural zone on the Baie Verte Peninsula. The St. Anthony outcrop samples are quite distinct from samples from the other areas, in that they contain more aluminium, exhibit an enriched flat HREE pattern, and were less altered in thin section. The St. Anthony samples clearly represent ultramafic rocks derived from a different mantle source and have not undergone the same alteration intensity as the other outcrop (or artifact) groups. None of the artifact groups analysed in this study have geochemical signatures that would be derived by altering the St. Anthony harzburgite parent lithology. The Trout River Pond and Tablelands outcrop samples appear very similar to one another in terms of their geochemical patterns and petrography. Both areas have a negative Nb anomaly, variations in LREE and HREE concentrations that broadly overlap with outcrop samples from Fleur de Lys. However, there is a pronounced enrichment in Th and consistently lower Nb concentrations for the Trout River and Tablelands samples compared to Fleur de Lys. There are no known Dorset quarry sites in ultramafic rocks at St. Anthony, Tablelands or Trout River. However, the primary geochemical signatures of these different areas are sufficiently distinctive that if carbonatised areas did exist that were quarried in the past, the expected geochemical signatures (i.e., immobile Nb, enriched Th, LREE) might be recognisable.

In this study, the Cape Ray and Port au Choix artifacts have geochemical patterns that preclude their being derived from the Fleur de Lys quarry, but their Nb, Th, and LREE and HREE features also preclude them from being derived from the Tablelands or

Trout River areas. For example, Cape Ray artifacts have too high a Nb concentration, and Port au Choix artifacts have too high HREE concentrations to be related to the Tablelands or Trout River areas. It remains speculative as to a possible outcrop source for the Port au Choix and Cape Ray artifacts; however there are other known ultramafic outcroppings along the coast in western Newfoundland. For example, the Blow Me Down and Lewis Hills massifs are located approximately 40-80 km south of Gros Morne National Park, and there are fault-bounded slivers of ultramafic rocks in the southwest corner of the island near Port aux Basques. These have not yet been surveyed for their geochemical compositions or archaeological significance.

5.4 Multiple Soapstone Sources and Sub-populations of Artifacts

Although the idea of multiple sources of artifacts is introduced in Chapter Four, careful inspection of the REE patterns (Fig. 4.9 to 4.16) reveals that within a particular group of artifacts, there exists sub-populations based on subtle differences in the REE patterns.

Within the Cape Ray artifact REE patterns (Fig. 4.9) two sub-groups exist based on REE concentrations and specific features. Two of the six artifacts tested from this site exhibit a lack of Nb anomaly and slight HREE enrichment (i.e., C2896 and C2824). The artifacts may have originated at a not-yet-identified quarry in southwest Newfoundland.

Most of the REE patterns of the artifacts from Englee (i.e., six of eight artifacts) have U-shaped REE patterns (Fig. 4.10), and overlap generally with Fleur de Lys artifacts E826 and E2044 (Fig. 4.14). One of the eight artifacts tested is very enriched in the LREE and has similar LREE abundances as artifacts E1346 and E1661 from Fleur de Lys

(Fig. 4.14). It is proposed that the raw material for the Englee artifacts originated at the Fleur de Lys quarry.

All the extended REE patterns of the Fleur de Lys artifacts exhibit Th enrichment, a negative Nb anomaly, and slight to pronounced LREE enrichment. Consequently, it is possible to identify three sub-groups based on differences in LREE concentrations (Fig. 4.11): E1346 and E1661 have a pronounced LREE enrichment and a slightly positive slope; E1663 has an intermediate LREE enrichment with a positive slope and linear trend; and E826 and E2044 have a U-shaped trend. The artifacts in this group were extracted from one of the Fleur de Lys quarry localities.

The Pittman site artifacts all have Th enrichment, LREE enrichment, and a U-shaped REE pattern (Fig. 4.12). The shape of this REE pattern and REE abundances of these artifacts are similar to the two U-shaped REE patterns of E826 and E2044 artifacts from Fleur de Lys and overlapping REE concentrations with E1663 from Fleur de Lys (Fig.4.15). Therefore, it is proposed that the artifacts from the Pittman site are derived from the quarry at Fleur de Lys.

Most of the REE patterns of the Port au Choix artifacts are enriched in Th, have a slight to pronounced negative Nb anomaly, have a generally linear trend and enriched HREEs (Fig. 4.16). Two artifacts have a slight HREE enrichment, E4833 and E4542, above the other artifacts. One of the seven artifacts tested, E3967, is U-shaped and is more depleted in REEs. The source of these artifacts is unknown.

5.5 Who Utilised the Fleur de Lys Quarry?

Until fairly recently it was assumed by the archaeological community that Fleur de Lys was the predominant, if not the only, source of Dorset soapstone artifacts in Newfoundland. Following the findings of this study, it is clearly apparent that this is not the case. Some of the soapstone vessels sampled here do not have their origins at Fleur de Lys and this is evidenced by the distinctive geochemical features described in the preceding sections and Chapter Four.

There is no strong geochemical evidence to support the mixing of artifact populations from Port au Choix, Cape Ray, and Fleur de Lys sites. This could be interpreted to indicate that there were distinct Dorset groups, each with their respective geochemically distinct quarry sites, that did not exchange soapstone materials. Conversely, the Englee, Pittman, and Fleur de Lys artifact groups have many geochemical affinities suggesting the Dorset groups responsible for these artifacts interacted and likely quarried from the same source at Fleur de Lys.

5.5.1 Theories of Soapstone Exchange

Prehistoric exchange is defined as "the spatial distribution of materials from hand to hand and from social group to social group" (Earle 1982: 2). To investigate exchange, Earle (1982: 2) identifies three tasks for the archaeologist:

a) source the objects of exchange;

b) describe the distribution of the objects;

c) reconstruct the organisation of the prehistoric exchange.

It is difficult to determine the mechanisms of distribution or the nature of exchange relationships. However, in many historic cultures, soapstone has been of economic significance and an important trade item. Boas (1964:61) discusses trade routes and goods amongst the western tribes of Boothia and the Aivillirmiut (the Central Eskimo) and points out that "visitors come from every part of the country" to obtain the soapstone and "trifles" were provided in exchange for the soapstone (Boas 1964:61). The hypothesis that long distance soapstone trading networks were in operation in the United States is supported by the recovery of soapstone artifacts from many prehistoric sites in Florida, Louisiana, Mississippi, New Jersey, and New York, where soapstone quarries do not exist (Luckenbach et al.1975b:189). In particular, a "Late Archaic steatite [soapstone] trade network" based on INAA data is discussed, defined as part of the "Poverty Point Interaction Sphere" in the Lower Mississippi Valley, Ohio, and Georgia (Smith 1974).

This study has attempted to define the source of soapstone and to identify the distribution of the Fleur de Lys quarry soapstone; with soapstone being the object of exchange. It has been determined that until all possible soapstone quarries are documented in Newfoundland it is not possible to make definite conclusions about soapstone distribution and exchange. Based on raw material types other than soapstone (e.g., Ramah chert), there is evidence of interaction between Dorset groups in Newfoundland and Labrador (Renouf 1999). However, this may be due to the limited availability of Ramah chert, and while the possibility of soapstone exchange in Newfoundland still exists, the multitude of soapstone outcrops in Labrador and unexplored ultramafic rock outcrops in Newfoundland restrict exploring the concept of exchange at this time.

5.6 If Not from Fleur de Lys, Then Where?

Considering that an impressive soapstone quarry exists within a few days journey of any habitation site in western Newfoundland, it could be assumed the Dorset would have quarried soapstone from the quarry at Fleur de Lys. However, following the findings of this study, it is apparent that many soapstone artifacts from western Newfoundland, and perhaps from the rest of the island as well, did not originate at Fleur de Lys. This is further supported by Erwin's (2001)[2] research which proposed that an average of four vessels per year were manufactured from the soapstone at the Fleur de Lys quarry. This small number seems quite modest in view of the amount of soapstone recovered from many Dorset sites on the island, particularly Phillip's Garden (Port au Choix) and Cape Ray. If the Dorset did not get their soapstone from Fleur de Lys (as evidenced by the geochemical signatures), where did they get the soapstone to manufacture their vessels?

At a conceptual level there are two issues to consider. These are based almost entirely on field reconnaissance. Extensively altered ultramafic rocks fitting the description of soapstone are not identified on most geological maps and are not noted by geologists in the field as a matter of course. There are however eight talc localities on the island, from the Burin Peninsula to the Baie Verte Peninsula. Coupled with this is the

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[2] Erwin's (2001) research was based on the idea that the quarry was used continuously for 400 years and considers the number of preform scars on the quarry face, the expected number of courses removed from that face(s), and a vessel use-life of 20 years.

lack of archaeological surveys conducted thus far in much of Newfoundland, particularly in the interior. Consequently, until every peridotite-derived rock outcrop is investigated for signs of prehistoric quarrying, it is not possible to present an exhaustive description of every soapstone quarry utilised by prehistoric peoples in Newfoundland, nor is it reasonable to disregard the possibility that there may be one or more other quarries on the island.

Another notion to be considered is that perhaps some of the soapstone utilised by the Dorset in Newfoundland originated at one of the many sources in Labrador. There were no samples of Labrador soapstone included in this study. This idea is in keeping with research that proposes that prehistoric groups in Newfoundland had contact with Labrador groups, as evidenced by 'exotic' lithic materials found in Maritime Archaic, Groswater and Dorset contexts in Newfoundland, in addition to raw materials from Newfoundland appearing at sites outside the island (Renouf 1999). Ramah chert from northern Labrador has been recovered at many sites in Newfoundland and chert from the Port au Port Peninsula and Cow Head have been recovered at Groswater sites in Labrador and Quebec (Renouf 1999: 413). Renouf (1999: 414) cites similar stylistic attributes as evidence for interaction between groups across the Strait of Belle Isle. A variety of similar tool forms, including soapstone vessels, triangular endblades and nephrite gravers, appear in Labrador and Newfoundland Dorset contexts (see Jordan 1986). Although Dorset groups in Newfoundland often utilised local fine-grained cherts in the construction of some tools such as endblades, it is conceivable that raw materials were not exclusively procured from sources in Newfoundland.

5.7 Robbins's Regional Variants Theory

The regional variants theory proposed by Robbins (1985) developed out of excavations and the subsequent interpretation of the Dorset site at Stock Cove in Trinity Bay. Stock Cove is anomalous in that it is a large habitation site located in the innermost part of Trinity Bay, an unusual location for a Dorset site, as it does not provide ready access to harp seals which is the core of the Dorset diet. This is inconsistent with the other large Dorset habitation sites Port au Choix and Cape Ray, which lie close to the sea and in view of the seals. This triggered Robbins to investigate Dorset site characteristics in Newfoundland based on the information from excavations available in 1985 and he concluded there are at least three regional Dorset populations on the island of Newfoundland: the Western, Northeastern, and Southern Expressions. The Dorset artifacts recovered from these areas exhibit different lithic artifact attributes and raw materials and different settlement and subsistence strategies reflect localised ecological conditions in each of the three regions (Robbins 1985:138). The West coast Dorset variant, which includes the west coast and northeast coast of the Great Northern Peninsula, exploited seals throughout the year, including harp seals in spring, harbour and grey seals in summer and autumn, and ringed seals in winter. The diet was augmented by salmon and other fishing while terrestrial hunting was limited. These Dorset typically occupied large habitation sites, for example Port au Choix. Endblades are shorter, wider, and typically made of Cow Head cherts. The Northeast Expression of Dorset, who occupied the Bonavista Bay area, also placed emphasis on sea mammals, but tended to have specialised camps (e.g., hunting, butchering) and were more mobile. The endblades from such sites are larger than the west coast variants and are made of rhyolite. The southern variant occupied the area from the Isthmus of Avalon to Cape Ray and the Dorset in that area exploited a wider variety of resources, including sea mammals, and mainly had small camps. Quartz crystal is used and grinding is seen on harpoon endblades.

Most Dorset sites fit into one of the variant groups; however, the locations of Cape Ray and the Pittman site place them at the boundaries between the West and South Coast variants and the West and Northeast variants, respectively, and therefore exhibit characteristics seen in each of these groups (Robbins 1985).

Since 1985, when Robbins originally proposed the notion of regional variants of the Dorset in Newfoundland, many additional sites have been excavated and more archaeological evidence has been recovered and interpreted. Recent research by Erwin (2000) and LeBlanc (2000) has further explored the hypothesis and augmented Robbins' interpretations using endblade characteristics from Fleur de Lys, Dildo Island and St. Pierre.

Robbins' regional variants are broadly in concert with the identified sub-populations of artifacts represented in this study. The Northeast coast variant would include Englee, Fleur de Lys, and the Pittman site while the West coast variant would incorporate Cape Ray and Port au Choix. Although Robbins does not directly mention Fleur de Lys, the results of this research places Fleur de Lys into the same group as Englee and the Pittman site. As it cannot be assumed that all artifacts from any particular site originated at the same quarry, it is thus logical to suggest the existence of other, as yet unknown, soapstone quarries/outcrops.

5.8 The Advantages of Using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) over Instrumental Neutron Activation Analysis (INAA) for Characterising Soapstone Artifacts

Trace element geochemistry compliments mapping, structural analysis, geophysics, and has even wider applications for interdisciplinary studies. In particular, ICP-MS has revolutionalised trace element geochemistry by allowing highly sensitive multi-element analyses. There are many advantages of ICP-MS over other techniques for multi-element analyses, especially for samples with low concentrations of REEs. These include:

- Low element detection limits
- Can analyse 60 elements simultaneously
- Linear range of 10^3 to 10^4
- External calibration with pure standards
- Isotope dilution

In previous provenance studies of soapstone which utilise INAA, it is notable that INAA has relatively high detection limits (LODs) when compared to ICP-MS, and therefore is not the most useful analytical technique for making REE determinations of soapstone (Fig. 5.1). When Moffat and Buttler (1986) employed INAA and radiochemical neutron activation analysis (RNAA) to geochemically source soapstone, they found RNAA to be sensitive to low REE abundances, while few REEs could be detected using INAA. They concluded that the "rare earth element concentrations [in soapstone] are too low for most elements to be determined reliably by instrumental neutron activation analysis (INAA)" (Moffat and Buttler 1986: 113-114).

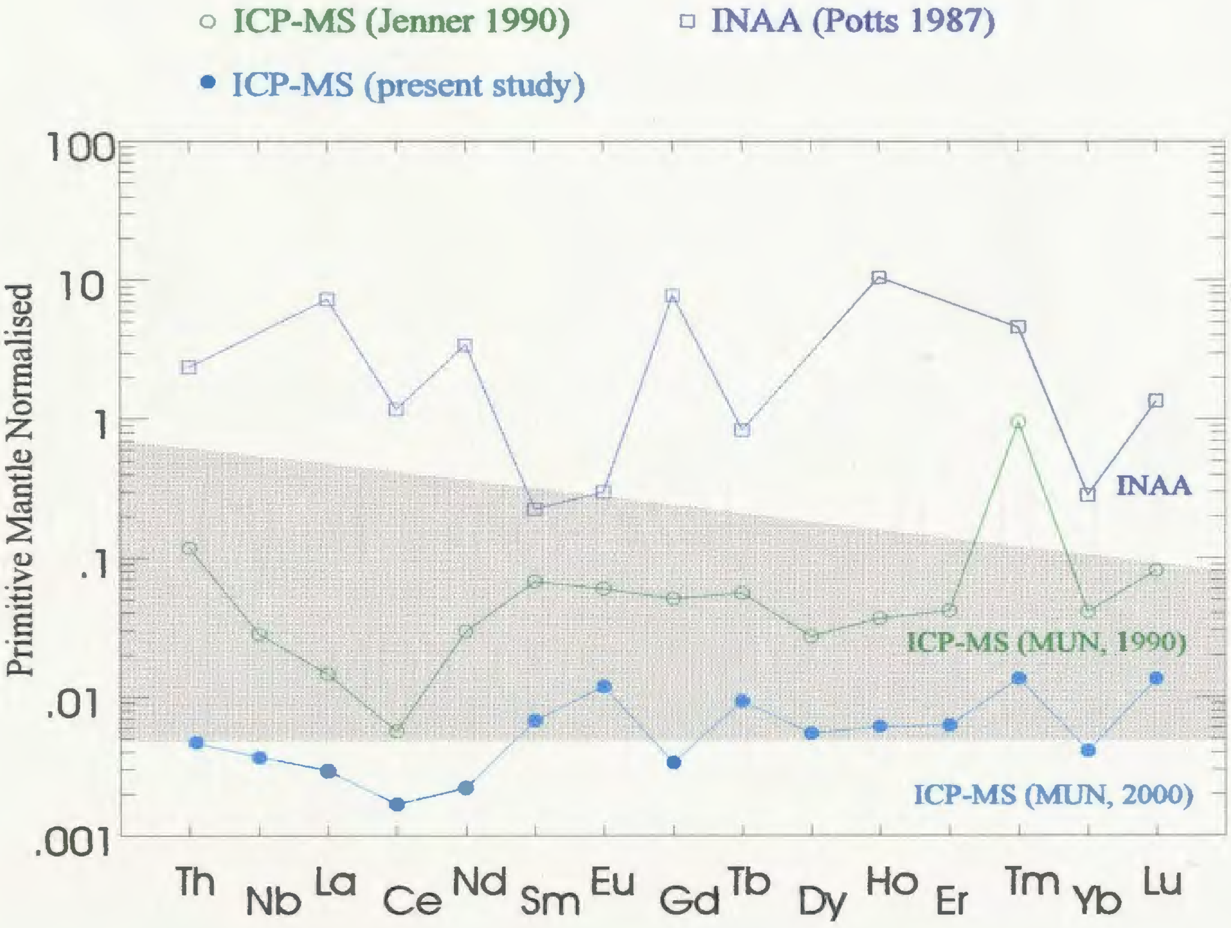

Figure 5.1: A Comparison of INAA detection limits for Potts (1987), ICP-MS detection limits for Jenner (1990), and ICP-MS detection limits for the present study. In all instances, the best data is reported. The grey shading represents the range of Th, Nb, and REE concentrations in the soapstone artifacts, as determined by ICP-MS in this study. It is clear that INAA does not have the analytical sensitivity necessary to determine REE concentrations in soapstone.

When INAA is used to determine REE abundances in soapstone, the analytical detection limits are rarely reported for each element, in fact, rarely are detection limits discussed at all (e.g., Holland et al. 1981; Luckenbach et al. 1975a; Luckenbach et al. 1975b). Therefore it is impossible to ascertain from many of these soapstone studies whether the data is near or below the analytical LODs, which prevents any meaningful comparative analyses. The LOD for INAA is, on average, almost a 1000 times higher compared to LODs obtained in this study (Fig. 5.1), and, on average, 10 times higher than typical concentrations in actual artifacts. Thus, the soapstone artifacts in Newfoundland cannot be analysed for Th, Nb, and REEs using INAA methods, or older ICP-MS instruments that also have elevated LODs (Fig. 5.1). The only major previous study of Newfoundland soapstone artifacts by Nagle (1982) used INAA techniques, but did not report the data in a unit of concentration that could be converted for comparison to this study. Moreover, Nagle (1982) did not report any LODs, and given the elevated LODs for typical INAA data (Fig. 5.1), it is uncertain what, if anything, the INAA REE data quantitatively represent.

5.9 Observations and Challenges of this Study

- The heavy rare earth elements (HREEs) were more immobile and reliable for identifying primary igneous protolith compositions than the light rare earth elements (LREEs). The LREEs were affected by alteration but yielded consistent REE patterns useful for provenance determinations. Th and Nb were also useful elements for characterising artifact groups.

- Experimenting with different dissolution methods to get REE abundances above ICP-MS detection limits was needed for some samples and as technology improves, new ICP-MS instruments should have lower LODs, making analysis of soapstone artifacts much more routine.
- Employing complimentary analytical techniques to more fully characterise the artifacts and to then apply the findings to an archaeological research question. Petrographic analysis was difficult due to the lack of primary mineral textures and XRD was useful for identifying ambiguous minerals. XRF was used to supplement REE ICP-MS analysis, providing major element data. All four steps were imperative to the acquisition of the representative geochemical and mineralogical signature(s).
- In general, mantle rocks have low concentrations of REEs nearing detection limits of analytical techniques. The effects of intense alteration (CO_2 metasomatism), increased Th and REE abundances which lessened the analytical problems for the ICP-MS.
- Employ analytical techniques relevant to the research question. ICP-MS has very low detection limits (see comparison of analytical detection limits in Appendix 2) and is useful for rocks that have undergone fluid alteration.
- Systematic sampling procedure based on careful examination outcrops and rocks in hand sample. Heterogeneity within outcrops will be selected for and should be a consideration when sampling any soapstone outcrop (e.g., Dorset selected softest soapstone for their implements). In particular, the geochemical variation between the Fleur de Lys outcrop and artifacts demonstrate that the outcrop should have been sampled directly at the quarry face.

- Obtain ‘fresh’ rock sample, that is, remove external weathering patina.
- Use ultrapure distilled acids for dissolution and for instrument runs to increase the sensitivity of the analysis.
- Immobile Nb can be used as an alteration index; HFSE, HREEs can provide geochemical signature(s); use mobile elements cautiously, e.g., Rb, Cs, Th, LREEs can be considered mobile in intensely altered (carbonatised) samples.
- Consider geological history of outcrop(s) in terms of element fractionation and REE behaviour.
- Multielement normalised diagrams have many advantages for interpretation over binary and ternary plots and are possible when ICP-MS data is used.
- Consider the depositional environment of artifacts. If an artifact was retrieved from a wet environment there is a possibility some external alteration of the mobile elements has occurred since initial burial. (e.g., the elevated Sr concentrations seen in the Englee artifacts).
- Investigate and utilise geochemical and other analytical techniques on other possible ultramafic outcrops, to determine suitability for quarrying. For example, survey the potential outcrop area near Port aux Basques to look for the source of the Cape Ray artifacts. Ultramafic outcrops in Labrador should also be investigated.

5.10 Conclusion

Metamorphosed ultramafic rocks have been little studied by the geological community as a result of element mobility and low REE concentrations. This research has succeeded in petrographically and chemically characterising soapstone artifacts and outcrops and serves to provide both geological and archaeological communities with valuable information about extensively altered ultramafic rocks, and has proven the potential for provenance studies of this nature within an archaeological context. For the archaeologist, provenance studies supply data sets that can be used to identify raw material distribution, indirectly provide information about prehistoric technology and the utilisation of lithic raw materials, and potentially infer trade routes. The amount of information that can be acquired through lithic provenancing studies far outweighs the limited destructive testing. In addition, in many cases debitage can be utilised, which spares complete artifacts.

For this study, thirty-three artifacts were collected from five Dorset sites: Cape Ray, Englee, Fleur de Lys, Pittman, and Port au Choix. Thirteen outcrop samples were collected from Fleur de Lys, St. Anthony, Straitsview, Tablelands, and Trout River. A summary of the major findings is presented in the following paragraphs.

Through petrographic analysis it is shown that magnesite and talc account for 40-50% of almost all samples. Chromium spinel is present in concentrations of 5-15% in some samples. Two distinct artifact populations have been identified: Cape Ray and Port au Choix, through the presence of significant chlorite (clinochlore) and the lack of carbonate minerals. Relict olivine is present in Trout River and St. Anthony outcrop samples, which reflects the primary igneous mineralogy.

It has been shown that inductively coupled plasma-mass spectrometry (ICP-MS) is a more sensitive technique than instrumental neutron activation analysis (INAA) for REE determinations of soapstone. INAA cannot achieve the low instrument detection limits possible with ICP-MS.

Artifact sub-populations are defined based on Th, Nb, and REE patterns. REE abundances, LREE and HREE slopes, and the shape of the REE patterns are used to classify specific sub-groups. Some of the REEs are mobile (i.e., LREEs) while the HREEs are immobile during fluid alteration. The Th and LREE enrichment seen in almost all REE patterns of artifact samples is also documented in the Th and LREE patterns of the Trout River and Tablelands outcrop samples. This enrichment, although an indication of element mobility, is consistent and can be used as a diagnostic feature of the samples.

St. Anthony, Tablelands, and Trout River outcrops are not a source of any of the Dorset artifacts tested. These outcrops are distinctive based on different primary igneous features, as identified in REE patterns. However, the sample set is small and it might be that other rock types with differing distinct chemistry are also present in these large mantle-derived massifs. Therefore, it cannot be ruled out that outcrops, more similar to the artifacts sampled, occur elsewhere in these large peridotite massifs.

The findings of this thesis provide preliminary evidence to address concepts of trade and exchange. Dorset groups from Cape Ray and Port au Choix were not travelling to Fleur de Lys to obtain soapstone for manufacturing their lamps and cooking pots. However, the source of soapstone artifacts at these sites is not known. There is geochemical evidence to support localised quarrying of the Fleur de Lys outcrop by Dorset groups from the Pittman and Englee sites.

The defined sub-populations are compared to Robbins (1985) regional variants theory for the Dorset in Newfoundland. The sub-populations correspond nicely with previous research based on raw material and tool morphology (i.e., endblades) undertaken by archaeologists investigating the distribution and regional variants of the Dorset in Newfoundland (Erwin 2000; LeBlanc 2000; Robbins 1985).

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APPENDIX ONE

Petrography

Petrographic analysis involves using a binocular petrographic microscope to examine thin sections of samples to identify mineral composition. The thin sections are 30 micron thick slices of rock glued to a microscope slide. By identifying the minerals in these rocks it is possible to differentiate the rocks based on optical properties prior to geochemical analysis. This step enables a greater understanding of the mineralogical compositions of the rocks and the amount of alteration that has taken place in each of the rocks during its geological and recent exposure history. Rocks are thus assembled into groups based on mineralogical characteristics. Examining rocks in thin section enables a preliminary examination of the mineral components of the rock.

Metamorphosed, serpentinised, and carbonatised rocks like soapstone often have minerals that are fine-grained in thin section causing difficulty in identification and XRD is used to accurately identify minerals present in individually selected rock units.

Site	Artifact	Composition	Comments
Cape Ray	CjBt-1:2897	Talc: 40-45% Chlorite: 40% Magnesite: 15-20%	Talc is in masses-very fine-grained
Cape Ray	CjBt-1:3121	Talc: 40-45% Chlorite: 35% Magnesite:10-15% Spinel: 5-10%	
Cape Ray	CjBt-1:2896	Talc: 60-70% Chlorite: 30% Spinel: 5-10%	
Cape Ray	CjBt-1:2801	Talc: 50% Chlorite: 40% Magnesite: 5% Spinel: 5%	
Cape Ray	CjBt-1:2824	Talc: 60-70%	Massive talc – very

		Spinel: 5-15% Chlorite: <15%	fine-grained
Cape Ray	CjBt-1:2898	Talc: >50% Chlorite: 30% Serpentine: 5-10% Spinel: 10%	
Englee 1	EeBa-1:1318	Talc: 40% Magnesite: 40% Spinel: 5-10% Serpentine: 10-15%	Very weathered
Englee 2	EeBa-2:752	Magnesite: 45% Talc: 35% Serpentine: 10% Spinel: 10%	
Englee 2	EeBa-2:762	Talc: 45% Magnesite: 45% Spinel: 10%	Very fine-grained
Englee 3	EeBa-3:682	Albite: 40% Quartz: 40% Muscovite: 5-10% Spinel: 5%	Not an artifact
Englee 3	EeBa-3:682-1	Talc: 50% Magnesite: 20-25% Serpentine: 10-15% Spinel: 5-10%	
Englee 3	EeBa-3:698	Talc: 40% Magnesite:40% Serpentine: 10-15% Spinel: 5-10%	Fine-grained
Englee 3	EeBa-3:699	Talc: 45% Magnesite: 40% Serpentine: 10% Spinel: 5%	
Englee 3	EeBa-3:697	Magnesite: 45% Talc: 45% Serpentine: 5% Spinel: 5%	Grains are large towards other samples
Fleur de Lys	EaBa-1: 826	Magnesite: 40% Talc: 50% Serpentine: 5% Spinel: 5%	Talc matrix, talc in magnesite cleavage
Fleur de Lys	EaBa-1: 1346	Magnesite: 45% Talc: 45% Serpentine: 5%	

		Spinel: 3% Quartz: 2%	
Fleur de Lys	EaBa-1: 1661	Magnesite: 45% Talc: 40% Quartz: 10% Spinel: 5%	
Fleur de Lys	EaBa-1: 1663	Talc: 40% Serpentine: 30% Magnesite: 25% Spinel: 5%	Talc grains are visible
Fleur de Lys	EaBa-1: 2044	Talc: 50% Magnesite: 25% Serpentine: 20% Spinel: 5%	Large magnesite grains
Pittman Site	DkBe-1: 793	Magnesite: 50% Talc: 40% Serpentine: 2% Spinel: 3% Quartz: 5%	Bladed talc bordering magnesite; well-defined lobes of magnesite; single blades of serpentine visible
Pittman Site	DkBe-1: 1020	Magnesite: 45% Talc: 50% Quartz: 5%	1-2mm magnesite grains (rhombs)
Pittman Site	DkBe-1: 149	Talc: 50-60% Magnesite: 30% Serpentine: 10% Spinel: 5% Quartz: 5%	Talc is in fibrous aggregates with some blades visible and is replacing magnesite at cleavage planes and boundaries; serpentine in masses
Pittman Site	DkBe-1: 150	Magnesite: 45% Talc: 45% Spinel: 5% Quartz: 5%	Large magnesite grains; can see blunt ends of talc
Pittman Site	DkBe-1: 1019	Magnesite: 45% Talc: 50% Spinel: 5%	Talc: 0.1 x 0.5mm long; magnesite grains are 1mm rhombs
Port au Choix	EeBi-1: 19040	Talc: 40-45% Chlorite: 40% Magnesite: 15-20%	
Port au Choix	EeBi-1: 4833	Talc: 50-60% Chlorite: 20-30% Quartz: 10% Spinel: 5%	
Port au Choix	EeBi-1: 19078	Talc: 45% Chlorite: 40%	Magnesite in lobes or rhombs;

		Magnesite: 10% Spinel: 5%	talc/magnesite boundaries are irregular; talc/chlorite interspersed; talc is massive/fibrous
Port au Choix	EeBi-1: 3967	Talc: 45% Magnesite: 35% Chlorite: 15% Spinel: 5%	
Port au Choix	EeBi-1: 3952	Talc: 50% Chlorite: 35% Magnesite: 5% Spinel: 5% Quartz: 5%	
Port au Choix	EeBi-1: 4542	Talc: 50% Chlorite: 25% Magnesite: 15% Spinel: 10%	Large minerals; talc matrix with chlorite; talc is in large masses – multidirectional
Port au Choix	EeBi-1:14128	Talc: 50% Chlorite: 25% Magnesite: 15% Spinel: 5-10%	Very fine-grained

Outcrop	**Sample**	**Composition**	**Collection information**
Fleur de Lys	FDL-1	Serpentine: 60% Magnesite: 27% Talc: 10% Spinel: 3%	Locality One; 20m south of main outcrop (& pot scars); on top of outcrop
Fleur de Lys	FDL-2	Serpentine: 60% Magnesite: 27% Talc: 10% Spinel: 3%	Locality One; 4-5m from sample 1 in same area; vein running North-South on rock
Fleur de Lys	FDL-3	Serpentine: 60% Magnesite: 27% Talc: 10% Spinel: 3%	Locality One; Same rock unit as main quarry face but further north along trail
Fleur de Lys	FDL-4	Serpentine: 40% Magnesite: 30% Talc: 20% Spinel: 5-10%	Locality Three (East of Locality One); on top of outcrop (above pot scars)
Fleur de Lys	FDL-5	Serpentine: 85% Talc: 5% Magnesite: 5% Spinel: 5%	Locality Three (above pot scars); 2-3 metres south of sample 4
St Anthony	Anth-1	Serpentine: 40-45%	Collected on trail;

(Howe Harbour)		Olivine: 30% Orthopyroxene: 20% Spinel: 5-10%	approx. 30m west of Howe Harbour & 1km south of TCH (route 430)
St Anthony (Howe Harbour)	Anth-2	Serpentine: 40-45% Olivine: 30% Orthopyroxene: 20% Spinel: 5-10%	Approx. 100m up on east side of Mt. Mer (Howe Hr.) & 500m south of sample 1; approx. 1.75km south of TCH (route 430)
St Anthony (Howe Harbour)	Anth-3	Serpentine: 40-45% Olivine: 30% Orthopyroxene: 20% Spinel: 5-10%	Same as #2 but 10m south
Straitsview	STR	Serpentine: 80% Oxides: 20%	Within the community of Straitsview (near road)
Tablelands 1	Table 1	Serpentine: 40% Olivine: 35% Orthopyroxene: <20% Spinel: 5-8%	200m straight above parking lot
Tablelands 2	Table 2	Serpentine: 40% Olivine: 35% Orthopyroxene: <20% Spinel: 5-8%	200m above parking lot & 50m east of sample 1
Trout River 1	TR1	Serpentine: 45% Olivine: 30% Talc: <20% Spinel: 5-8%	5km along Trout River trail and 150m above south bank of Trout River
Trout River 2	TR2	Serpentine: 45% Olivine: 30% Talc: <20% Spinel: 5-8%	Same as above
Bear Cove Road	CO981	Serpentine: 50% Talc: 20-25% Orthopyroxene: <20% Spinel: 10%	Approx. 1km west of road junction; at road cut; Baie Verte Peninsula

X-Ray Powder Diffraction Procedure

XRD scans and provides peak listings for fourteen artifact and outcrop samples (pages A1-8 to A1-31). Minerals were assigned according to their corresponding peaks.

The x-axis represents the 2-theta angle of the measured peak while the y-axis represents the counts (i.e. the strength) of the peak. Identified mineral peaks are listed at the bottom of each scan and each scan represents one sample.

The peak listings represent the number of significant and diagnostic peaks in the scan (numbered vertically on the lists). The peak position includes the 2-theta angle at which the peak appears in the scan. The centroid-position is the centre of the peak on the scan and the 2-theta angle at which this occurs. Within the *peak and area without background* section the areas of the peaks are important. Mineral ratios are determined by calculating AREA ratios and can be used to compare samples (i.e. samples that have the same minerals present). Only significant mineral areas are considered in the ratio determinations.

The *peaks* programme reports the AREA under each peak. Major peaks can be selected to represent each mineral present, and the AREA under each will be proportional to the % abundance present. By taking ratios of AREAs under different peaks, it is possible to discuss the relative increases or decreases of minerals in the rocks. For example, if the talc/carbonate ratio, or the serpentine/talc ratio, changes systematically among different sample groups, then XRD data should substantiate petrographic groups. The AREA data simply quantifies petrography and because the error is large only semi-quantitative statements can be made about the data.

XRD Procedure

Samples were removed from the specimens and ground to a fine powder in a mortar and pestle. The powder was mixed with acetone and spread onto glass slides and left to dry. Once dry the slides were labelled and then placed in the x-ray diffraction unit (Rigaku-200 sequential wave-length diffractometer) employing CuK radiation.

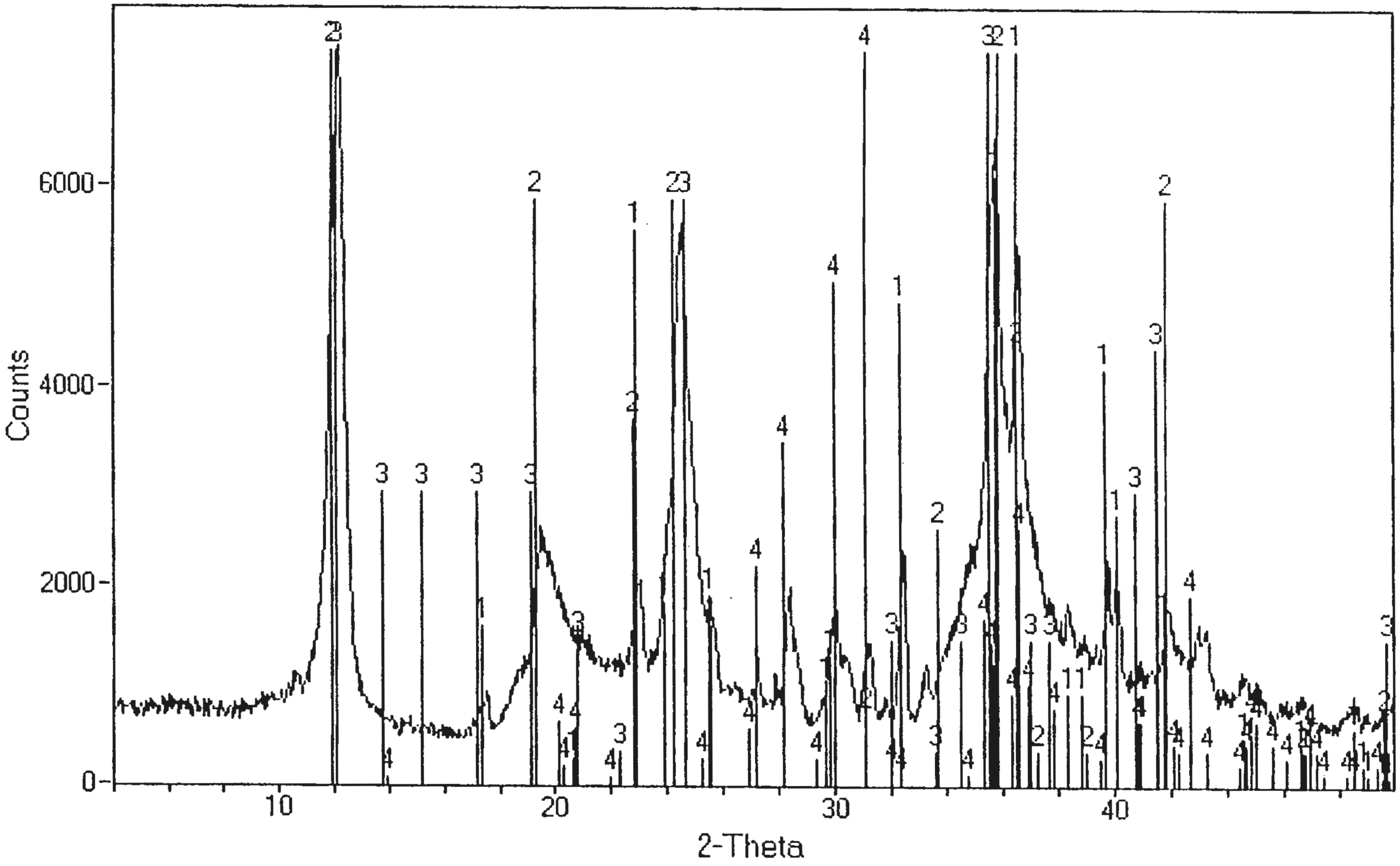
XRD Operating conditions (Scan Parameters):

Radiation	CU_1.54059
Scan Range (2-theta angle)	4-50°
Step Size	0.03°
Scan Speed	4°/minute

The software package JADE was used to identify mineral assemblages.

ID: ROUTINE ID. !

File: ANTH1.MDI   Scan: 4-49.96/.03/ .45/#1533, Anode: CU



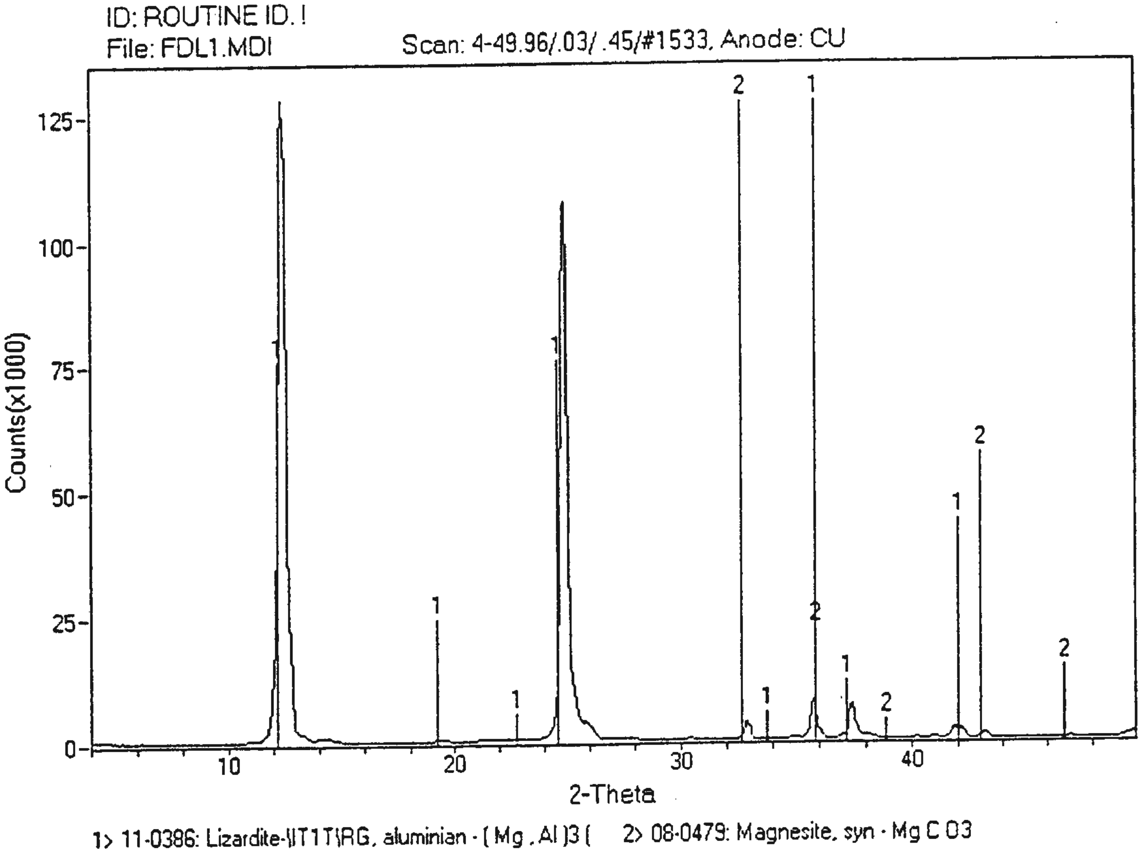
1> 34-0189: Forsterite, syn - Mg2 Si O4

2> 18-0779: Lizardite-\IT1T\RG - Mg3 Si2 O5 (O H)4

3> 21-0963: Antigorite-\IT1M\RG - Mg3 Si2 O5 (O H)4

4> 35-0610: Clinoenstatite, syn - Mg Si O3

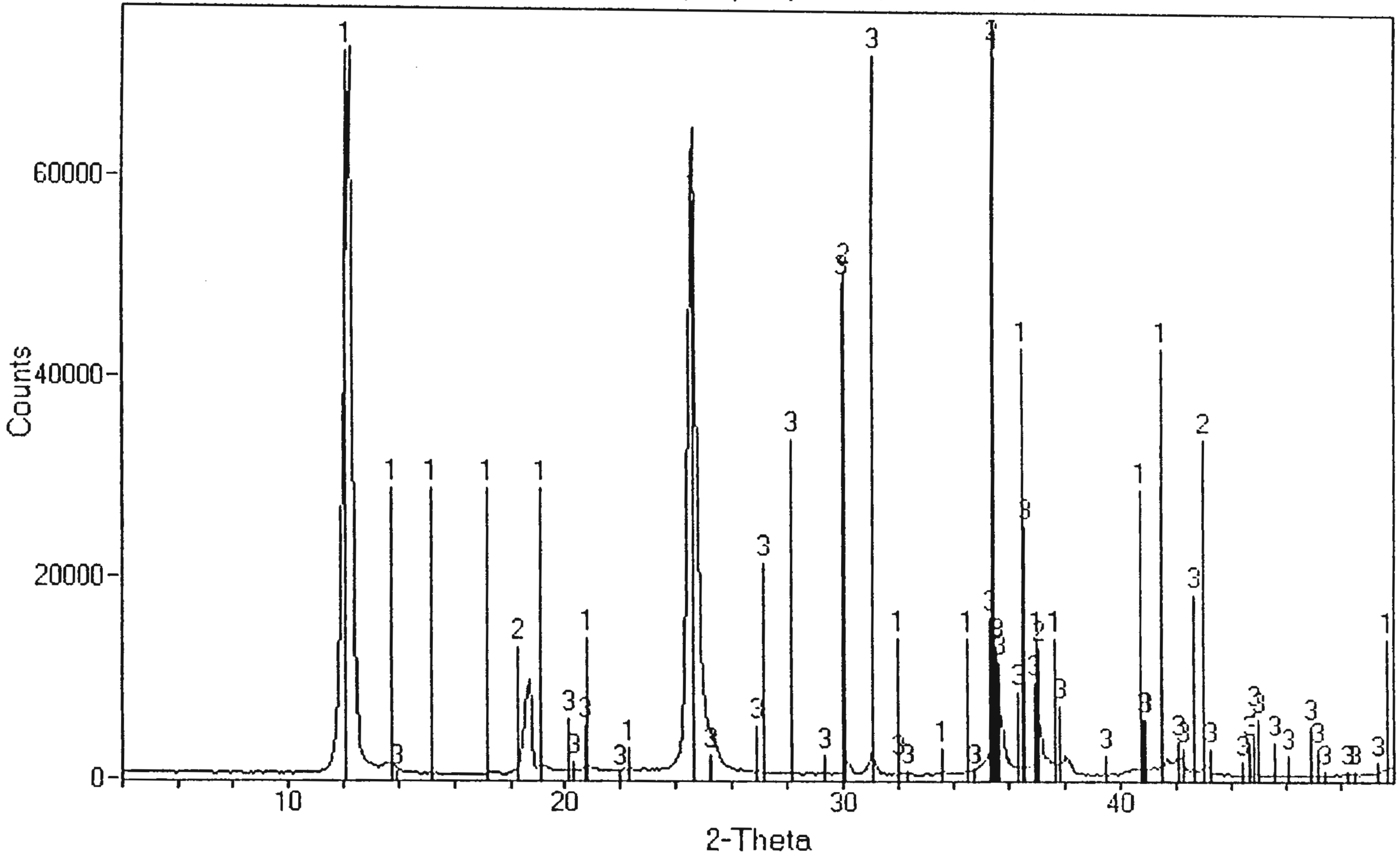
```
========================== MUN Earth Sciences ==========================
Jade: Peak Listing                                 Fri Sep 08 2000 @10:53am
===============================================================================
File: ANTH1.MDI> ROUTINE ID. !

----------- Scan Parameters: -------------------- Search Parameters: ---------
      Radiation  = CU_1.54059          ||    Filter length(pts)   = 25
      Scan Range = 4- 49.96            ||    Noise level(sigmas) = 3.0
      Step Size  = .03                 ||    Intensity cutoff(%) = .5-100
      Count Time = .45 sec.            ||    2-Theta Zero (degs) = 0
-------------------------------------------------------------------------------

      Peak-Position  Centroid-Position   Peak & Area are without Bkgrd
      -------------  -----------------  --------------------------------
 #    2Theta     d    2Theta      d      Bkgrd    Peak   I%     Area   I%    FWHM*
-------------------------------------------------------------------------------
 1:   12.160  7.2725  12.156  7.2752     716    6688 100.0    4531 100.0  0.610
 2:   17.501  5.0633  17.500  5.0638     531     331   4.9      83   1.8  0.226
 3:   19.452  4.5598  19.451  4.5599     867    1551  23.2     886  19.6  0.514
 4:   22.960  3.8703  22.942  3.8733    1201     792  11.8     288   6.4  0.327
 5:   24.490  3.6319  24.490  3.6319    1113    4425  66.2    3232  71.3  0.657
 6:   25.570  3.4809  25.569  3.4810    1072     677  10.1     199   4.4  0.265
 7:   27.187  3.2775  27.193  3.2767     807     515   7.7      68   1.5  0.119
 8:   28.357  3.1448  28.357  3.1448     740    1224  18.3     403   8.9  0.296
 9:   29.950  2.9810  29.955  2.9805     653    1165  17.4     514  11.3  0.397
10:   30.488  2.9297  30.484  2.9300     653     560   8.4     149   3.3  0.239
11:   31.179  2.8663  31.173  2.8668     653     771  11.5     286   6.3  0.334
12:   32.412  2.7600  32.392  2.7617     665    1651  24.7     463  10.2  0.252
13:   33.225  2.6943  33.222  2.6945     861     343   5.1      73   1.6  0.192
14:   35.740  2.5103  35.736  2.5105    1493    4883  73.0    3228  71.2  0.595
15:   36.609  2.4526  36.578  2.4547    1702    3734  55.8    1564  34.5  0.377
16:   38.350  2.3452  38.362  2.3445    1450     357   5.3      65   1.4  0.164
17:   39.972  2.2537  39.971  2.2538    1122     585   8.7     199   4.4  0.306
18:   40.146  2.2444  40.147  2.2443    1085     799  11.9     152   3.4  0.171
19:   41.861  2.1563  41.870  2.1559     950     850  12.7     260   5.7  0.275
20:   43.123  2.0960  43.106  2.0968     917     512   7.7     359   7.9  0.631
21:   44.595  2.0302  44.592  2.0304     787     246   3.7     104   2.3  0.380
-------------------------------------------------------------------------------
  * Intensity values are based on total raw counts.
```


ID: ROUTINE ID. !
File: FDL1.MDI
Scan: 4-49.96/.03/.45/#1533, Anode: CU
Counts(x1000)
0
25
50
75
100
125
10
20
30
40
2-Theta
1
2
1> 11-0386: Lizardite-\IT1T\RG, aluminian - (Mg , Al)3 (
2> 08-0479: Magnesite, syn - Mg C O3

```
============================ MUN Earth Sciences ==============================
Jade: Peak Listing                                    Wed Sep 20 2000 @1:50pm
==============================================================================
File: FDL1.MDI> ROUTINE ID. !

----------- Scan Parameters: -------------------- Search Parameters: ---------
      Radiation  = CU_1.54059          ||  Filter length(pts)  = 25
      Scan Range = 4-¯49.96            ||  Noise level(sigmas) = 3.0
      Step Size  = .03                 ||  Intensity cutoff(%) = .5-100
      Count Time = .45 sec.            ||  2-Theta Zero (degs) = 0
------------------------------------------------------------------------------

      Peak-Position  Centroid-Position   Peak & Area are without Bkgrd
      -------------  -----------------  ---------------------------------
  #   2Theta     d    2Theta     d       Bkgrd   Peak   I%     Area   I%   FWHM*
------------------------------------------------------------------------------
  1:  12.370  7.1499  12.394  7.1357    733  125292 100.0  55383 100.0  0.398
  2:  14.083  6.2835  14.082  6.2840    835     369   0.3     71   0.1  0.173
  3:  24.850  3.5801  24.857  3.5791    730  106854  85.3  44912  81.1  0.378
  4:  32.889  2.7211  32.881  2.7217    387    3557   2.8   1149   2.1  0.291
  5:  35.740  2.5103  35.768  2.5084    409    7700   6.1   2641   4.8  0.309
  6:  37.416  2.4016  37.418  2.4015    405    6575   5.2   2509   4.5  0.343
  7:  41.832  2.1577  41.852  2.1567    385    2424   1.9    795   1.4  0.295
------------------------------------------------------------------------------
  * Intensity values are based on total raw counts.
```

ID: ROUTINE ID. !

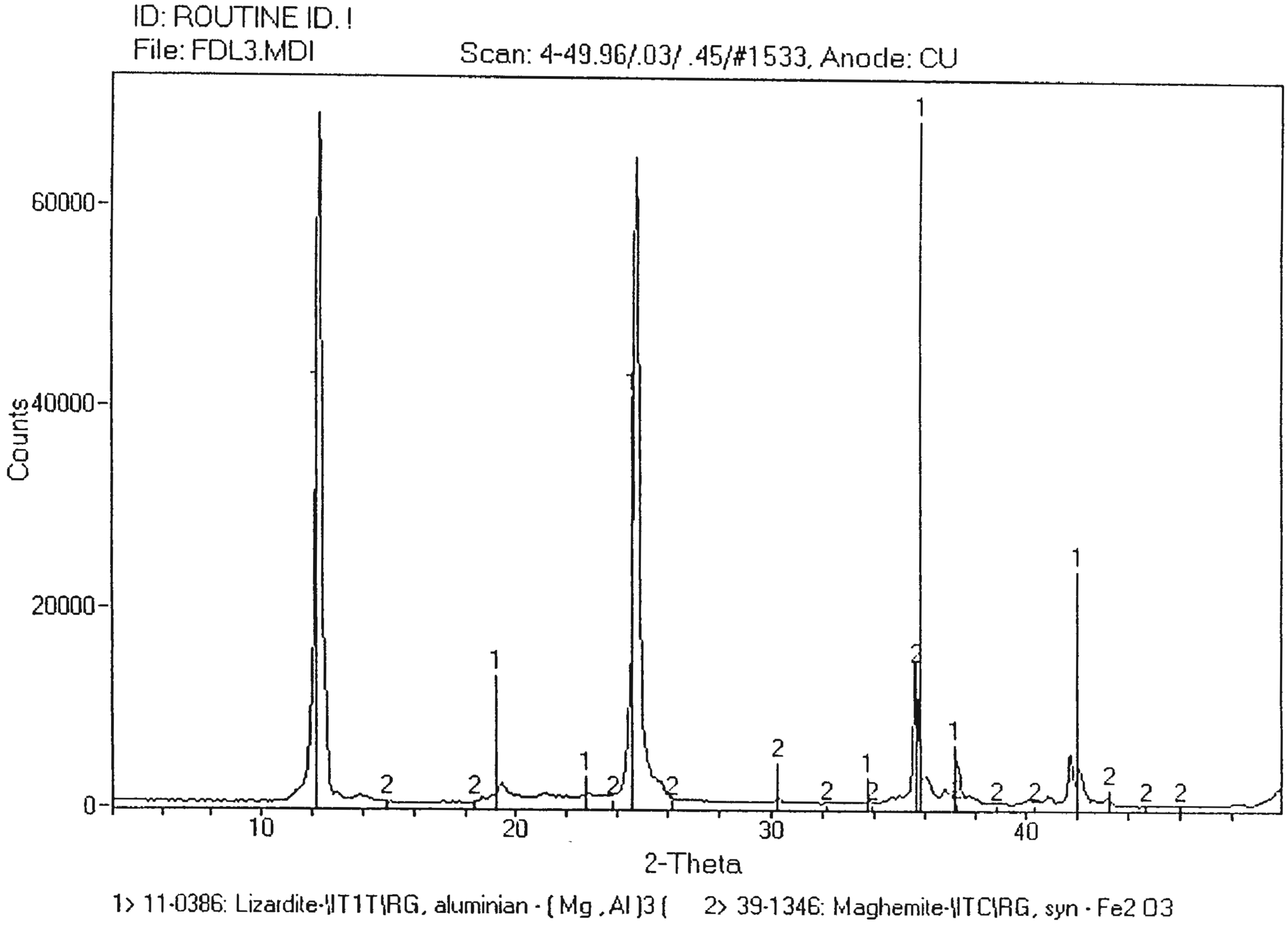
File: CO981.MDI   Scan: 4-49.96/.03/ .45/#1533, Anode: CU



1> 21-0963: Antigorite-\IT1M\RG - Mg3 Si2 O5 (O H)4   2> 19-0629: Magnetite, syn - Fe3 O4

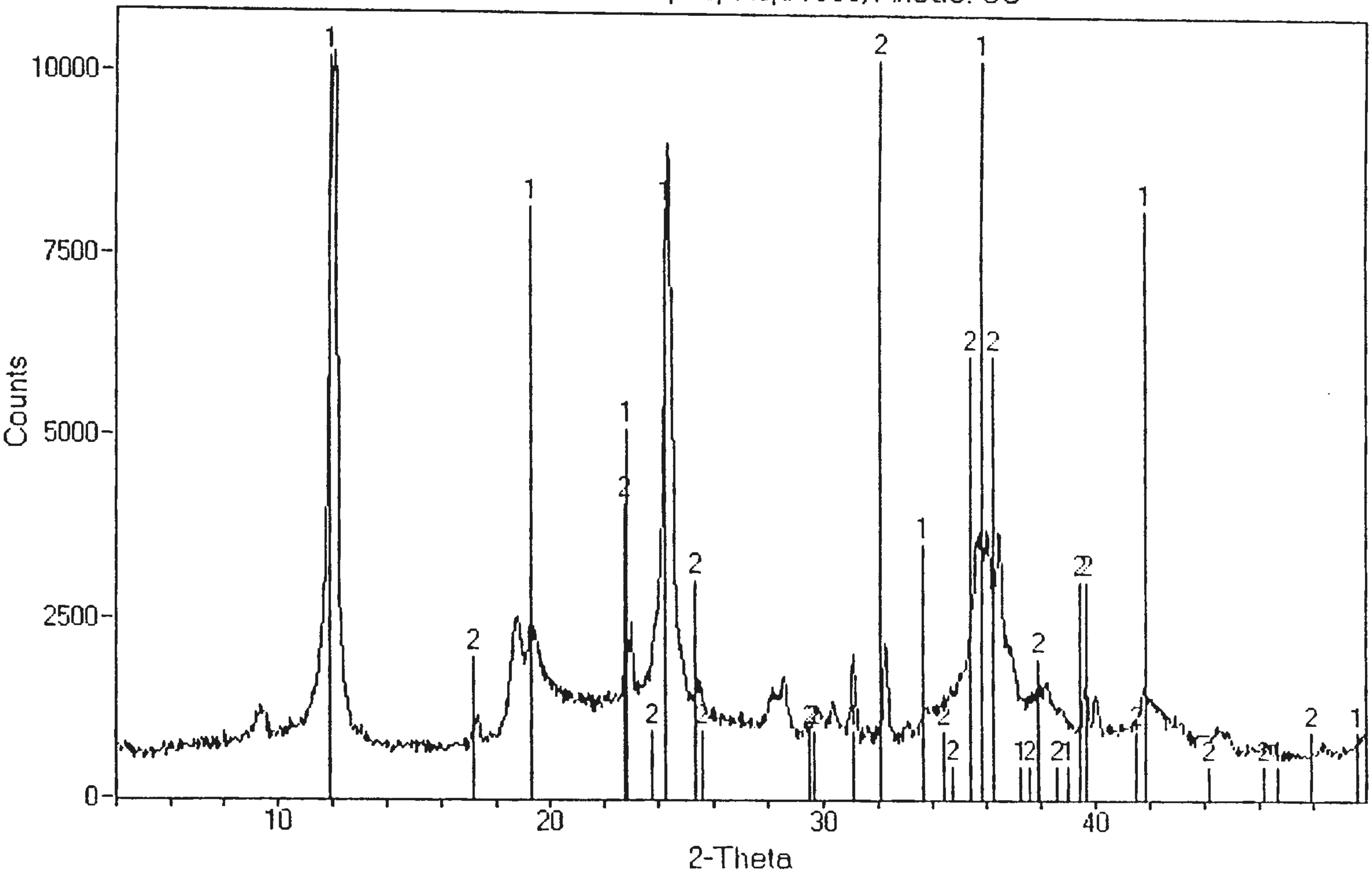
3> 35-0610: Clinoenstatite, syn - Mg Si O3

```
============================== MUN Earth Sciences ==============================
Jade: Peak Listing                                         Tue Sep 19 2000 @2:38pm
================================================================================
File: CO981.MDI> ROUTINE ID. !

----------- Scan Parameters: -------------------- Search Parameters: ----------
      Radiation  = CU_1.54059          ||    Filter length(pts)   = 25
      Scan Range = 4- 49.96            ||    Noise level(sigmas)  = 3.0
      Step Size  = .03                 ||    Intensity cutoff(%)  = .5-100
      Count Time = .45 sec.            ||    2-Theta Zero (degs)  = 0
--------------------------------------------------------------------------------

      Peak-Position   Centroid-Position   Peak & Area are without Bkgrd
      ------------- ------------------ ---------------------------------
  #   2Theta     d      2Theta      d       Bkgrd    Peak    I%     Area    I%    FWHM*
--------------------------------------------------------------------------------
  1:  12.251   7.2189  12.200   7.2487     667   70622 100.0  27118  99.3  0.346
  2:  18.671   4.7487  18.636   4.7575     673    9118  12.9   3020  11.1  0.298
  3:  24.611   3.6144  24.613   3.6141     945   64080  90.7  27302 100.0  0.383
  4:  30.158   2.9610  30.144   2.9624     565    1155   1.6    347   1.3  0.270
  5:  31.030   2.8797  31.021   2.8806     558    2211   3.1    650   2.4  0.265
  6:  35.533   2.5244  35.573   2.5217    1068    7832  11.1   3568  13.1  0.410
  7:  37.122   2.4199  37.152   2.4181    1063    4777   6.8   1470   5.4  0.277
  8:  42.043   2.1474  42.044   2.1473     614    1679   2.4    904   3.3  0.485
--------------------------------------------------------------------------------
  * Intensity values are based on total raw counts.
```


ID: ROUTINE ID. !
File: FDL3.MDI
Scan: 4-49.96/.03/ .45/#1533, Anode: CU
Counts
60000
40000
20000
0
10
20
30
40
2-Theta
1
2
1> 11-0386: Lizardite-\IT1T\RG, aluminian - (Mg , Al)3 (
2> 39-1346: Maghemite-\ITC\RG, syn - Fe2 O3

```
============================== MUN Earth Sciences ==============================
Jade: Peak Listing                                        Tue Sep 19 2000 @2:53pm
=================================================================================
File: FDL3.MDI> ROUTINE ID. !

----------- Scan Parameters: --------------------- Search Parameters: ----------
      Radiation   = CU_1.54059         ||     Filter length(pts)   = 25
      Scan Range = 4- 49.96            ||     Noise level(sigmas) = 3.0
      Step Size   = .03                ||     Intensity cutoff(%) = .5-100
      Count Time = .45 sec.            ||     2-Theta Zero (degs) = 0
---------------------------------------------------------------------------------

      Peak-Position   Centroid-Position   Peak & Area are without Bkgrd
      ------------- ----------------- ---------------------------------
  #   2Theta      d      2Theta      d       Bkgrd    Peak    I%      Area    I%     FWHM*
---------------------------------------------------------------------------------
  1:  12.281   7.2012  12.275    7.2050    657    68512  100.0   22695  100.0  0.298
  2:  19.419   4.5673  19.434    4.5639    764     1772    2.6     732    3.2  0.372
  3:  24.730   3.5972  24.725    3.5980   1040    63985   93.4   21462   94.6  0.302
  4:  30.221   2.9549  30.221    2.9550    567      597    0.9     102    0.4  0.154
  5:  35.648   2.5165  35.651    2.5164    952    14068   20.5    3856   17.0  0.247
  6:  37.269   2.4107  37.280    2.4100   1078     4018    5.9    1087    4.8  0.243
  7:  41.740   2.1622  41.757    2.1614    481     5043    7.4    1464    6.5  0.261
---------------------------------------------------------------------------------
  * Intensity values are based on total raw counts.
```

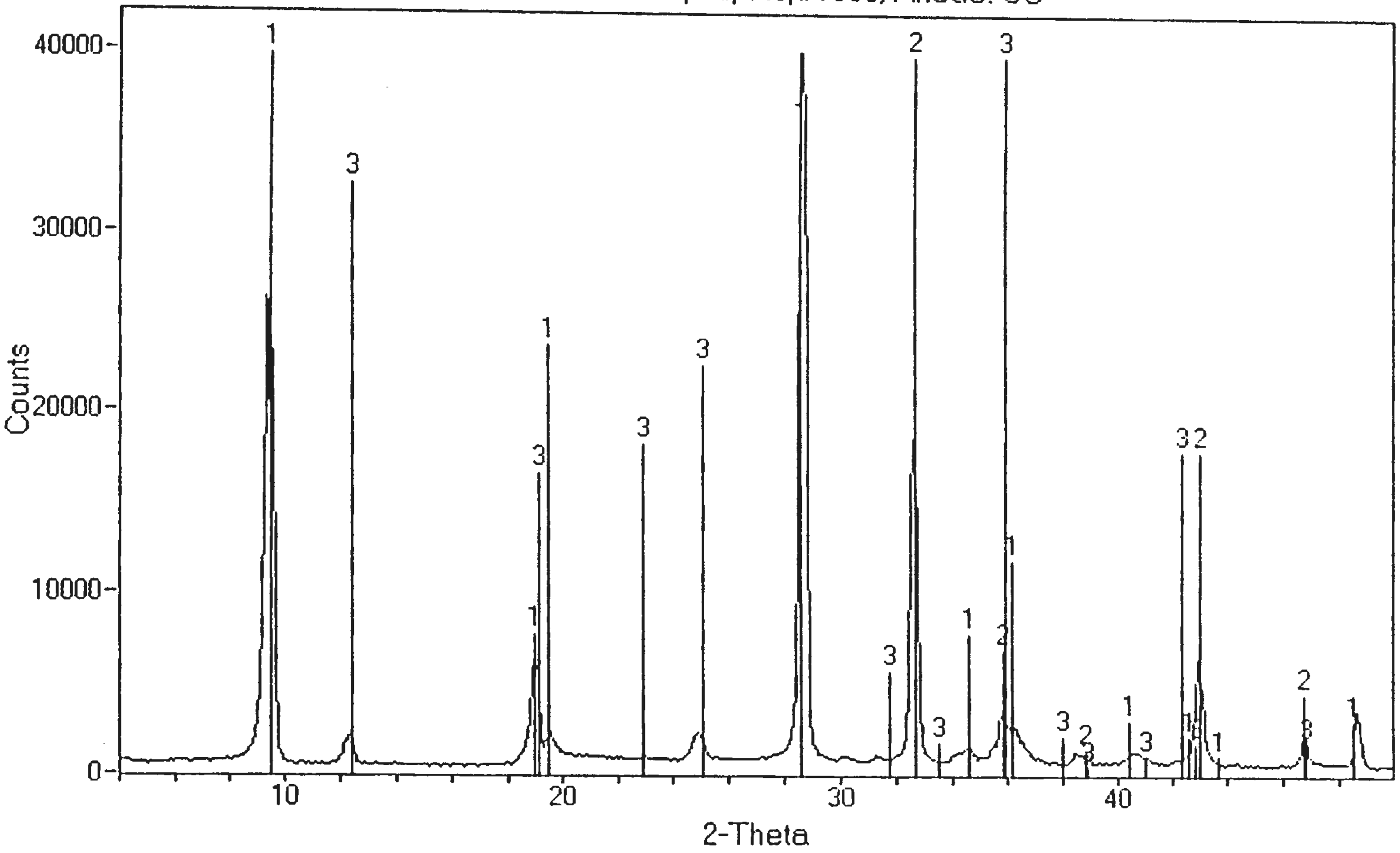
ID: ROUTINE ID. !
File: TROUT1.MDI Scan: 4-49.96/.03/ .45/#1533, Anode: CU



1> 18-0779: Lizardite-\IT1T\RG - Mg3 Si2 O5 (O H)4 2> 31-0795: Forsterite, ferroan - (Mg , Fe)2 Si O4

```
============================== MUN Earth Sciences ==============================
Jade: Peak Listing                                       Tue Sep 19 2000 @2:47pm
================================================================================
File: TROUT1.MDI> ROUTINE ID. !

----------- Scan Parameters: -------------------- Search Parameters: ----------
      Radiation  = CU_1.54059            ||     Filter length(pts)   = 25
      Scan Range = 4- 49.96              ||     Noise level(sigmas) = 3.0
      Step Size  = .03                   ||     Intensity cutoff(%) = .5-100
      Count Time = .45 sec.              ||     2-Theta Zero (degs) = 0
--------------------------------------------------------------------------------

      Peak-Position  Centroid-Position   Peak & Area are without Bkgrd
      -------------- ----------------- -------------------------------
  #   2Theta       d     2Theta      d        Bkgrd    Peak    I%     Area    I%    FWHM*
--------------------------------------------------------------------------------
  1:   9.371  9.4302   9.371  9.4300    902     405    4.3      36    0.8  0.080
  2:  12.070  7.3267  12.045  7.3419    839    9459  100.0    4245  100.0  0.404
  3:  18.760  4.7263  18.764  4.7253   1086    1445   15.3     682   16.1  0.425
  4:  19.358  4.5815  19.358  4.5817   1098    1304   13.8     801   18.9  0.553
  5:  22.956  3.8709  22.957  3.8709   1559     930    9.8     103    2.4  0.100
  6:  24.312  3.6580  24.311  3.6582   1282    7802   82.5    3127   73.7  0.361
  7:  28.390  3.1412  28.390  3.1412    984     572    6.0     134    3.2  0.211
  8:  32.261  2.7726  32.271  2.7717    899    1310   13.8     252    5.9  0.173
  9:  35.860  2.5021  35.861  2.5021   1345    2066   21.8    2132   50.2  0.929
 10:  36.461  2.4623  36.453  2.4628   1385    2339   24.7     802   18.9  0.309
 11:  39.641  2.2718  39.650  2.2713    990     730    7.7     151    3.6  0.186
 12:  40.197  2.2416  40.197  2.2416    934     164    1.7      11    0.3  0.060
 13:  41.768  2.1609  41.769  2.1608    894     648    6.9     226    5.3  0.314
--------------------------------------------------------------------------------
  * Intensity values are based on total raw counts.
```

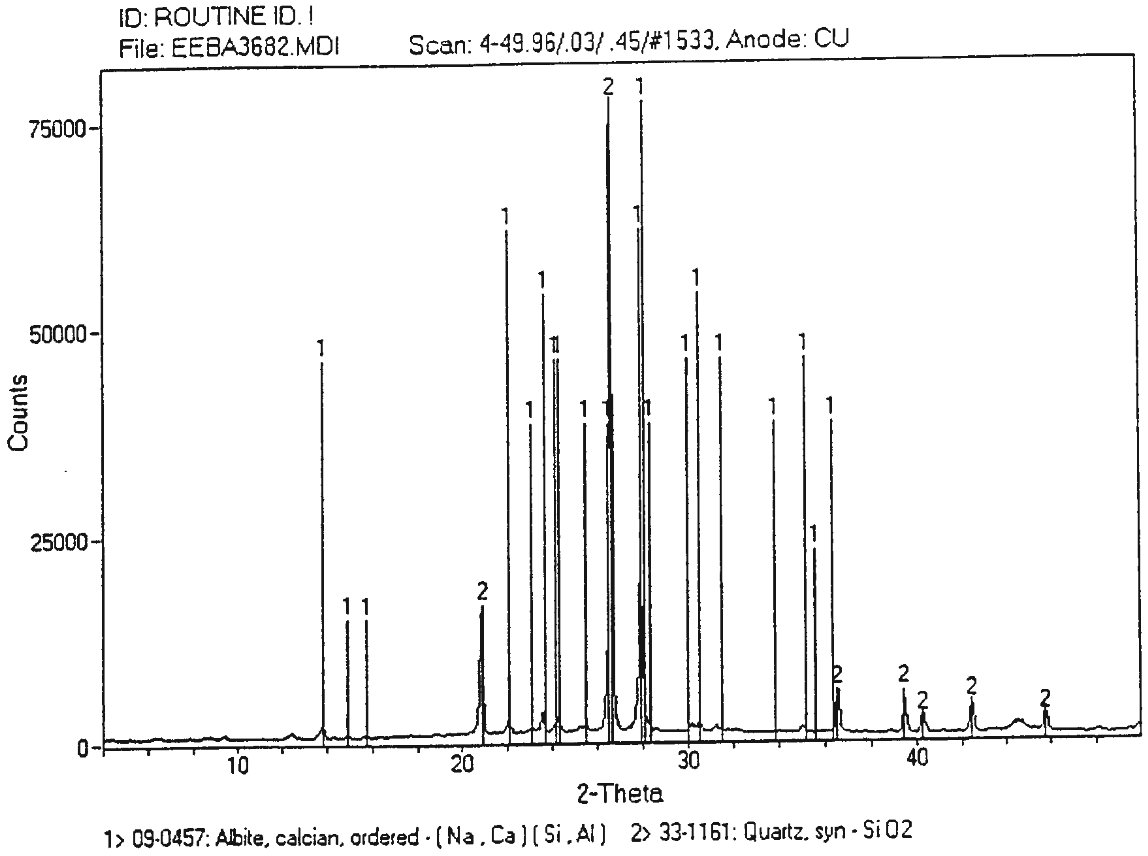
ID: ROUTINE ID. !
File: DKBE149.MDI Scan: 4-49.96/.03/.45/#1533, Anode: CU



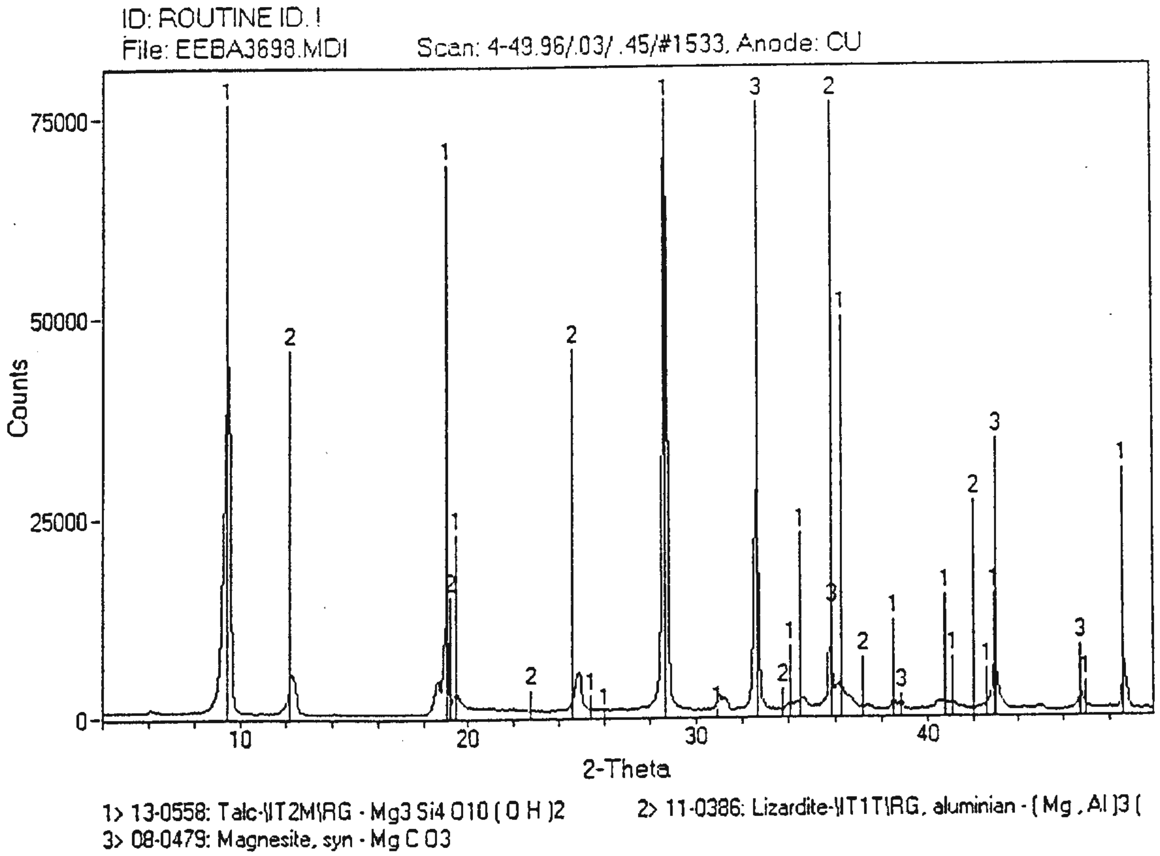
1> 29-1493: Talc-\IT2M\RG - Mg3 Si4 O10 (O H)2 2> 08-0479: Magnesite, syn - Mg C O3

3> 22-1161: Lizardite-\IT1T\RG, syn - Mg3 Si2 O5 (O H)

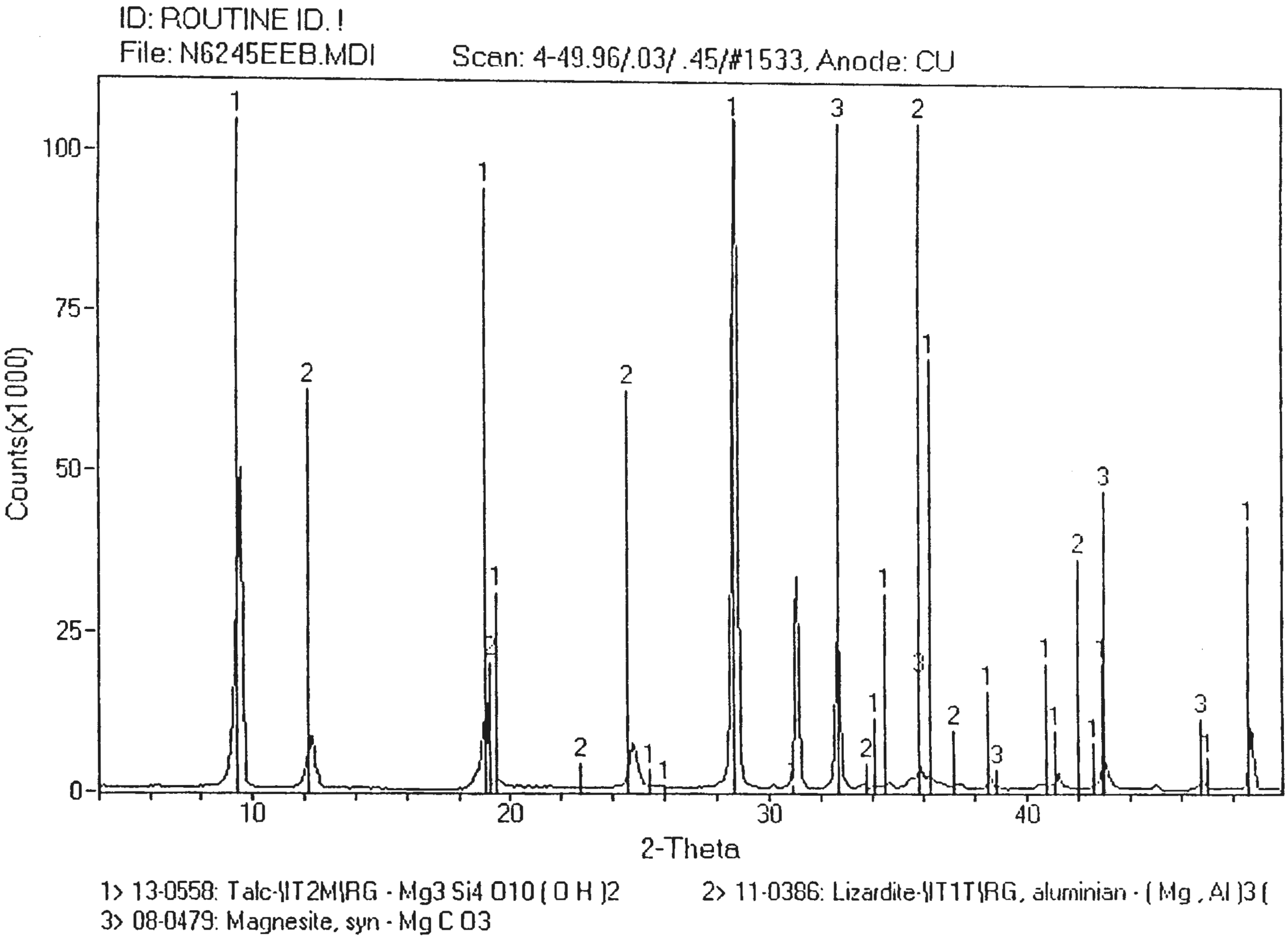
```
============================ MUN Earth Sciences ==============================
Jade: Peak Listing                                      Wed Sep 20 2000 @1:13pm
===============================================================================
File: DKBE149.MDI> ROUTINE ID. !

---------- Scan Parameters: -------------------- Search Parameters: ----------
      Radiation  = CU_1.54059          ||    Filter length(pts)   = 25
      Scan Range = 4-_49.96            ||    Noise level(sigmas)  = 3.0
      Step Size  = .03                 ||    Intensity cutoff(%)  = .5-100
      Count Time = .45 sec.            ||    2-Theta Zero (degs)  = 0
-------------------------------------------------------------------------------

      Peak-Position  Centroid-Position   Peak & Area are without Bkgrd
      -------------  ----------------- --------------------------------
  #   2Theta      d      2Theta      d       Bkgrd    Peak    I%     Area    I%    FWHM*
-------------------------------------------------------------------------------
  1:   9.371  9.4302   9.369  9.4319    640   25640  65.5    8951  68.2  0.314
  2:  12.341  7.1662  12.306  7.1867    516    1635   4.2     697   5.3  0.384
  3:  18.969  4.6746  18.959  4.6771    764    5318  13.6    2453  18.7  0.415
  4:  19.481  4.5529  19.482  4.5527    708    1692   4.3     877   6.7  0.466
  5:  24.970  3.5631  24.970  3.5631    867    1373   3.5     480   3.7  0.315
  6:  28.630  3.1154  28.636  3.1148    847   39153 100.0   13119 100.0  0.302
  7:  32.591  2.7453  32.599  2.7446    769   17787  45.4    5912  45.1  0.299
  8:  35.830  2.5042  35.845  2.5032    732    2961   7.6    1453  11.1  0.442
  9:  38.500  2.3364  38.500  2.3364    615     754   1.9     172   1.3  0.205
 10:  40.661  2.2171  40.665  2.2169    663     646   1.6     397   3.0  0.553
 11:  42.970  2.1031  42.977  2.1028    621    5843  14.9    2182  16.6  0.336
 12:  46.809  1.9392  46.815  1.9390    556    1697   4.3     590   4.5  0.313
 13:  48.645  1.8702  48.688  1.8687    551    3127   8.0     880   6.7  0.253
-------------------------------------------------------------------------------
 * Intensity values are based on total raw counts.
```


ID: ROUTINE ID. !
File: EEBA3682.MDI
Scan: 4-49.96/.03/.45/#1533, Anode: CU
Counts
75000
50000
25000
0
10
20
30
40
2-Theta
1
2
1> 09-0457: Albite, calcian, ordered - (Na , Ca) (Si , Al)
2> 33-1161: Quartz, syn - Si O2

```
============================ MUN Earth Sciences ============================
Jade: Peak Listing                                    Wed Sep 20 2000 @1:29pm
===========================================================================
File: EEBA3682.MDI> ROUTINE ID. !

---------- Scan Parameters: -------------------- Search Parameters: ---------
     Radiation  = CU_1.54059        ||    Filter length(pts)   = 25
     Scan Range = 4-¯49.96          ||    Noise level(sigmas) = 3.0
     Step Size  = .03               ||    Intensity cutoff(%) = .5-100
     Count Time = .45 sec.          ||    2-Theta Zero (degs) = 0
---------------------------------------------------------------------------

     Peak-Position  Centroid-Position   Peak & Area are without Bkgrd
     -------------  ----------------  -------------------------------
  #  2Theta       d     2Theta      d      Bkgrd   Peak    I%    Area   I%    FWHM*
---------------------------------------------------------------------------
  1: 12.487  7.0827  12.474   7.0904    721     675   0.9    170   1.1  0.227
  2: 13.812  6.4065  13.782   6.4204    733    1405   1.8    357   2.3  0.229
  3: 20.826  4.2618  20.796   4.2680   1162   14549  19.0   2818  18.3  0.174
  4: 22.028  4.0320  22.015   4.0343   1196    1608   2.1    281   1.8  0.157
  5: 23.521  3.7793  23.499   3.7827   1213    2340   3.1    502   3.3  0.193
  6: 24.160  3.6807  24.161   3.6807   1222    1629   2.1    394   2.6  0.218
  7: 25.234  3.5264  25.239   3.5259   1298     613   0.8    205   1.3  0.301
  8: 26.617  3.3463  26.592   3.3493   1244   76597 100.0  15385 100.0  0.181
  9: 27.884  3.1971  27.884   3.1970   1289   19949  26.0   4597  29.9  0.207
 10: 30.463  2.9320  30.457   2.9326   1070    1283   1.7    294   1.9  0.206
 11: 34.992  2.5622  34.991   2.5622    870     770   1.0    143   0.9  0.167
 12: 36.521  2.4584  36.536   2.4574    770    5308   6.9   1127   7.3  0.191
 13: 39.457  2.2819  39.464   2.2815    643    4257   5.6    828   5.4  0.175
 14: 40.270  2.2377  40.277   2.2373    664    2943   3.8    539   3.5  0.165
 15: 42.429  2.1287  42.451   2.1277    711    4073   5.3    855   5.6  0.189
 16: 44.590  2.0304  44.599   2.0300    686    1183   1.5    853   5.5  0.649
 17: 45.786  1.9801  45.787   1.9801    695    3018   3.9    559   3.6  0.167
 18: 48.157  1.8881  48.149   1.8884    603     473   0.6    106   0.7  0.202
 19: 49.947  1.8245  49.947   1.8245    598    1062   1.4     57   0.4  0.048
---------------------------------------------------------------------------
 * Intensity values are based on total raw counts.
```


ID: ROUTINE ID. !
File: EEBA3698.MDI
Scan: 4-49.96/.03/ .45/#1533, Anode: CU
Counts
75000
50000
25000
0
10
20
30
40
2-Theta
1> 13-0558: Talc-\IT2M\RG - Mg3 Si4 O10 (O H)2
2> 11-0386: Lizardite-\IT1T\RG, aluminian - (Mg , Al)3 (
3> 08-0479: Magnesite, syn - Mg C O3

```
============================= MUN Earth Sciences ===============================
Jade: Peak Listing                                          Wed Sep 20 2000 @1:33pm
================================================================================
File: EEBA3698.MDI> ROUTINE ID. !

----------- Scan Parameters: -------------------- Search Parameters: ----------
      Radiation  = CU_1.54059           ||    Filter length(pts)   = 25
      Scan Range = 4-_49.96             ||    Noise level(sigmas)  = 3.0
      Step Size  = .03                  ||    Intensity cutoff(%)  = .5-100
      Count Time = .45 sec.             ||     2-Theta Zero (degs)  = 0
--------------------------------------------------------------------------------

      Peak-Position  Centroid-Position   Peak & Area are without Bkgrd
      -------------- ----------------- --------------------------------
  #   2Theta      d      2Theta     d       Bkgrd    Peak    I%     Area    I%    FWHM*
--------------------------------------------------------------------------------
  1:    9.461  9.3408    9.416   9.3854     669   43431   57.3   16586   87.8  0.344
  2:   12.250  7.2192   12.243   7.2237     559    4963    6.5    1745    9.2  0.316
  3:   19.000  4.6671   18.973   4.6738     758   11304   14.9    3012   16.0  0.240
  4:   19.450  4.5601   19.456   4.5588     776    2522    3.3    1180    6.2  0.421
  5:   24.851  3.5800   24.824   3.5838     823    5061    6.7    1918   10.2  0.341
  6:   28.633  3.1151   28.631   3.1153     877   75852  100.0   18882  100.0  0.224
  7:   31.057  2.8773   31.077   2.8754     793    1656    2.2     788    4.2  0.428
  8:   32.592  2.7452   32.596   2.7448     824   27225   35.9    6886   36.5  0.228
  9:   35.744  2.5100   35.773   2.5080     830    7690   10.1    1971   10.4  0.231
 10:   36.159  2.4821   36.160   2.4821     898    3142    4.1    2518   13.3  0.721
 11:   38.527  2.3349   38.534   2.3345     666    1336    1.8     341    1.8  0.230
 12:   38.827  2.3175   38.828   2.3174     656    1155    1.5     243    1.3  0.189
 13:   40.630  2.2187   40.630   2.2187     723    1013    1.3     639    3.4  0.568
 14:   42.967  2.1033   42.970   2.1032     722    7065    9.3    2363   12.5  0.301
 15:   46.807  1.9393   46.813   1.9391     621    2199    2.9     657    3.5  0.269
 16:   48.649  1.8701   48.686   1.8687     641    5277    7.0    1279    6.8  0.218
--------------------------------------------------------------------------------
  * Intensity values are based on total raw counts.
```


ID: ROUTINE ID. !
File: N6245EEB.MDI
Scan: 4-49.96/.03/.45/#1533, Anode: CU
Counts(x1000)
0
25
50
75
100
10
20
30
40
2-Theta
1
2
3
1> 13-0558: Talc-\IT2M\RG - Mg3 Si4 O10 (O H)2
2> 11-0386: Lizardite-\IT1T\RG, aluminian - (Mg , Al)3 (
3> 08-0479: Magnesite, syn - Mg C O3

```
=========================== MUN Earth Sciences ============================
Jade: Peak Listing                                    Tue Sep 19 2000 @2:48pm
=============================================================================
File: N6245EEB.MDI> ROUTINE ID. !

----------- Scan Parameters: -------------------- Search Parameters: ----------
      Radiation  = CU_1.54059           ||    Filter length(pts)   = 25
      Scan Range = 4-¯49.96             ||    Noise level(sigmas)  = 3.0
      Step Size  = .03                  ||    Intensity cutoff(%)  = .5-100
      Count Time = .45 sec.             ||    2-Theta Zero (degs)  = 0
-------------------------------------------------------------------------------

      Peak-Position  Centroid-Position   Peak & Area are without Bkgrd
      ------------- ----------------- ---------------------------------
  #   2Theta     d      2Theta     d      Bkgrd   Peak   I%    Area   I%   FWHM*
-------------------------------------------------------------------------------
  1:   9.578  9.2270   9.494  9.3085    657   49519  47.8  16438  58.9  0.299
  2:  12.312  7.1835  12.276  7.2041    542    8340   8.0   3287  11.8  0.355
  3:  19.060  4.6526  19.021  4.6621    643   13750  13.3   5189  18.6  0.340
  4:  24.733  3.5968  24.765  3.5922    633    6894   6.6   2882  10.3  0.376
  5:  28.715  3.1064  28.676  3.1105    643  103686 100.0  27923 100.0  0.242
  6:  31.081  2.8751  31.060  2.8770    641   28523  27.5   6074  21.8  0.192
  7:  32.649  2.7405  32.636  2.7416    653   24560  23.7   6357  22.8  0.233
  8:  35.888  2.5003  35.887  2.5003    665    3559   3.4   1490   5.3  0.377
  9:  41.230  2.1878  41.225  2.1881    621    2726   2.6    703   2.5  0.232
 10:  43.000  2.1018  43.019  2.1009    639    5799   5.6   1940   6.9  0.301
 11:  46.810  1.9392  46.811  1.9391    476    1586   1.5    430   1.5  0.244
 12:  48.787  1.8651  48.788  1.8651    522    6727   6.5   1420   5.1  0.190
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  * Intensity values are based on total raw counts.
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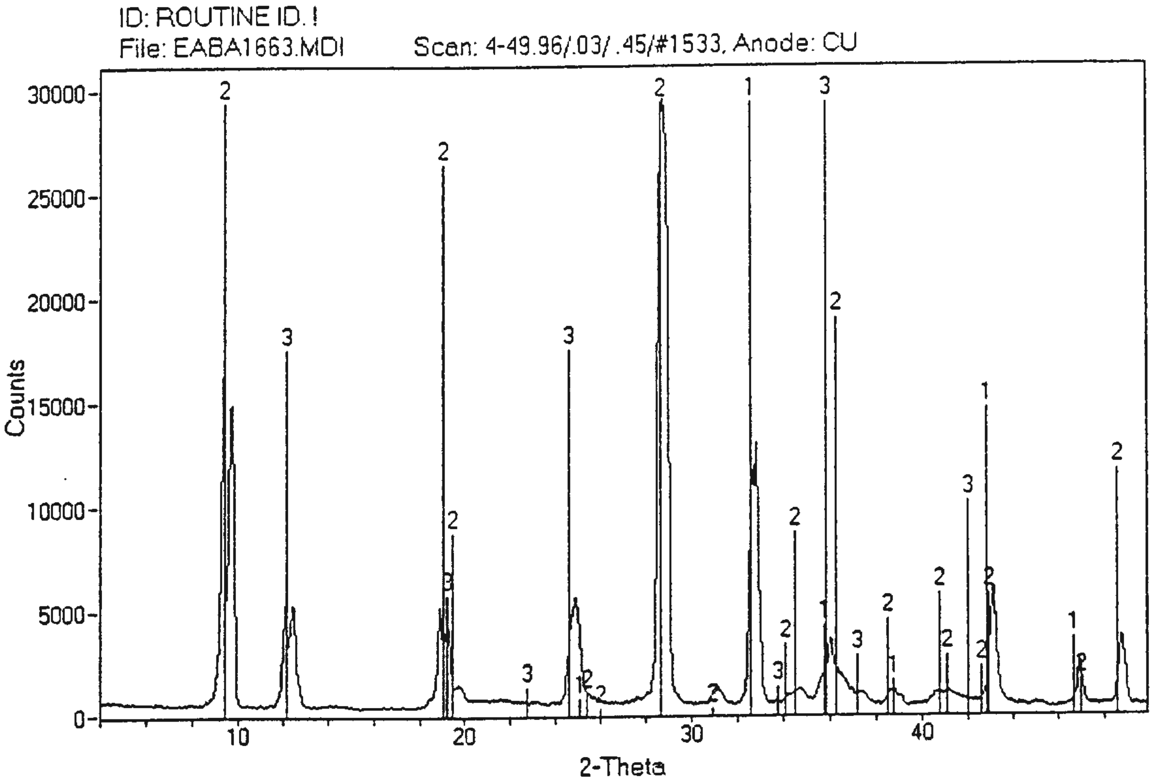

1> 36-0383: Magnesite, ferroan - (Mg , Fe) C O3
2> 13-0558: Talc-\IT2M\RG - Mg3 Si4 O10 (O H)2
3> 11-0386: Lizardite-\IT1T\RG, aluminian - (Mg , Al)3 (

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     ------------- ------------------ ------------------------------
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 1:    9.341  9.4602    9.341  9.4605     476   15837  55.5    3770  28.6  0.214
 2:   12.101  7.3083   12.104  7.3062     430    4866  17.0    1319  10.0  0.244
 3:   18.882  4.6961   18.884  4.6955     493    4689  16.4    1278   9.7  0.245
 4:   24.822  3.5841   24.816  3.5850     535    5074  17.8    3041  23.1  0.539
 5:   28.780  3.0995   28.780  3.0995     536   28560 100.0   13173 100.0  0.415
 6:   31.119  2.8717   31.116  2.8720     526     945   3.3     340   2.6  0.324
 7:   32.801  2.7282   32.800  2.7282     522   12458  43.6    3826  29.0  0.276
 8:   36.011  2.4920   36.013  2.4919     539    3103  10.9    1900  14.4  0.551
 9:   37.427  2.4009   37.427  2.4009     937     170   0.6       7   0.1  0.037
10:   38.710  2.3242   38.711  2.3242     400     727   2.5     372   2.8  0.461
11:   40.840  2.2078   40.804  2.2097     501     641   2.2     188   1.4  0.264
12:   43.147  2.0949   43.124  2.0960     528    5492  19.2    2172  16.5  0.356
13:   46.962  1.9333   46.963  1.9332     359    2259   7.9     654   5.0  0.261
14:   48.819  1.8640   48.810  1.8643     415    3258  11.4    1170   8.9  0.323
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  * Intensity values are based on total raw counts.
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A1-28

ID: ROUTINE ID. !

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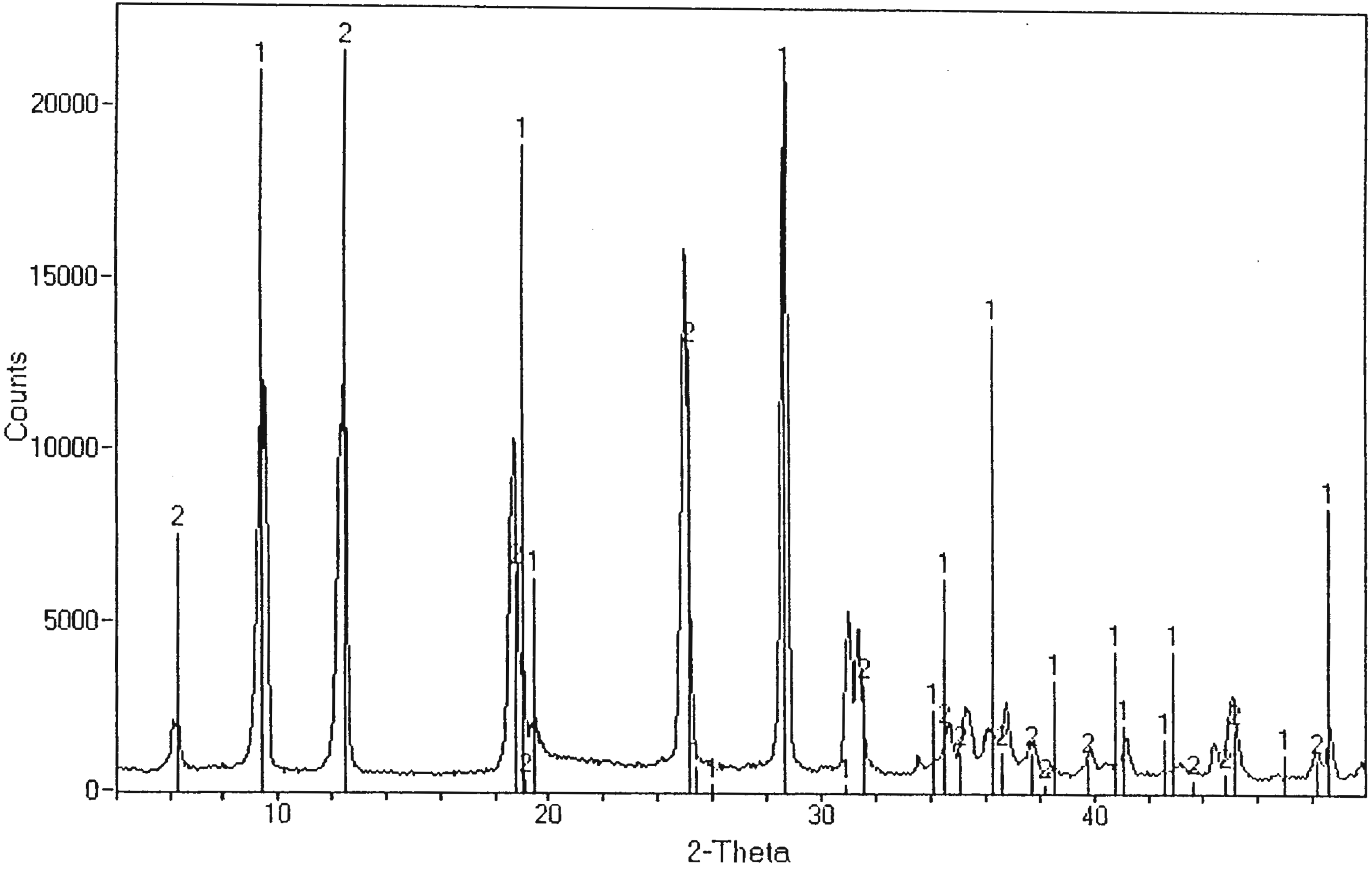

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  1:   6.186  14.2765    6.171  14.3112      622    1251   5.9     626  10.2  0.450
  2:   9.550   9.2534    9.549   9.2549      602   11349  53.6    2754  44.8  0.218
  3:  12.490   7.0813   12.489   7.0817      529   11838  55.9    3269  53.2  0.249
  4:  18.728   4.7342   18.712   4.7382      755    9545  45.1    3985  64.8  0.376
  5:  19.480   4.5533   19.478   4.5537      755    1467   6.9     738  12.0  0.453
  6:  24.999   3.5591   24.984   3.5613      740   15162  71.6    5175  84.2  0.307
  7:  28.660   3.1122   28.639   3.1144      662   21165 100.0    6145 100.0  0.261
  8:  31.001   2.8823   31.003   2.8822      584    4703  22.2    1506  24.5  0.288
  9:  31.360   2.8501   31.358   2.8503      572    4244  20.1    1598  26.0  0.339
 10:  33.519   2.6714   33.519   2.6714      670     450   2.1      54   0.9  0.108
 11:  34.630   2.5881   34.620   2.5889      846    1287   6.1     418   6.8  0.292
 12:  35.261   2.5432   35.282   2.5418      703    1855   8.8     893  14.5  0.433
 13:  36.041   2.4900   36.040   2.4900      837    1061   5.0     196   3.2  0.166
 14:  36.759   2.4430   36.737   2.4444      838    1862   8.8     699  11.4  0.338
 15:  37.719   2.3830   37.711   2.3835      747     802   3.8     247   4.0  0.277
 16:  38.503   2.3362   38.515   2.3355      540     362   1.7      70   1.1  0.174
 17:  39.850   2.2603   39.839   2.2609      510     883   4.2     336   5.5  0.342
 18:  41.199   2.1894   41.200   2.1894      550    1097   5.2     299   4.9  0.245
 19:  43.268   2.0893   43.268   2.0893      547     331   1.6      39   0.6  0.106
 20:  44.468   2.0357   44.478   2.0353      525    1017   4.8     324   5.3  0.287
 21:  45.128   2.0075   45.116   2.0080      482    2387  11.3    1055  17.2  0.398
 22:  48.219   1.8858   48.220   1.8857      443     833   3.9     334   5.4  0.361
 23:  48.695   1.8684   48.687   1.8687      450    1330   6.3     408   6.6  0.276
 24:  49.819   1.8289   49.819   1.8289      830     143   0.7       8   0.1  0.050
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  * Intensity values are based on total raw counts.
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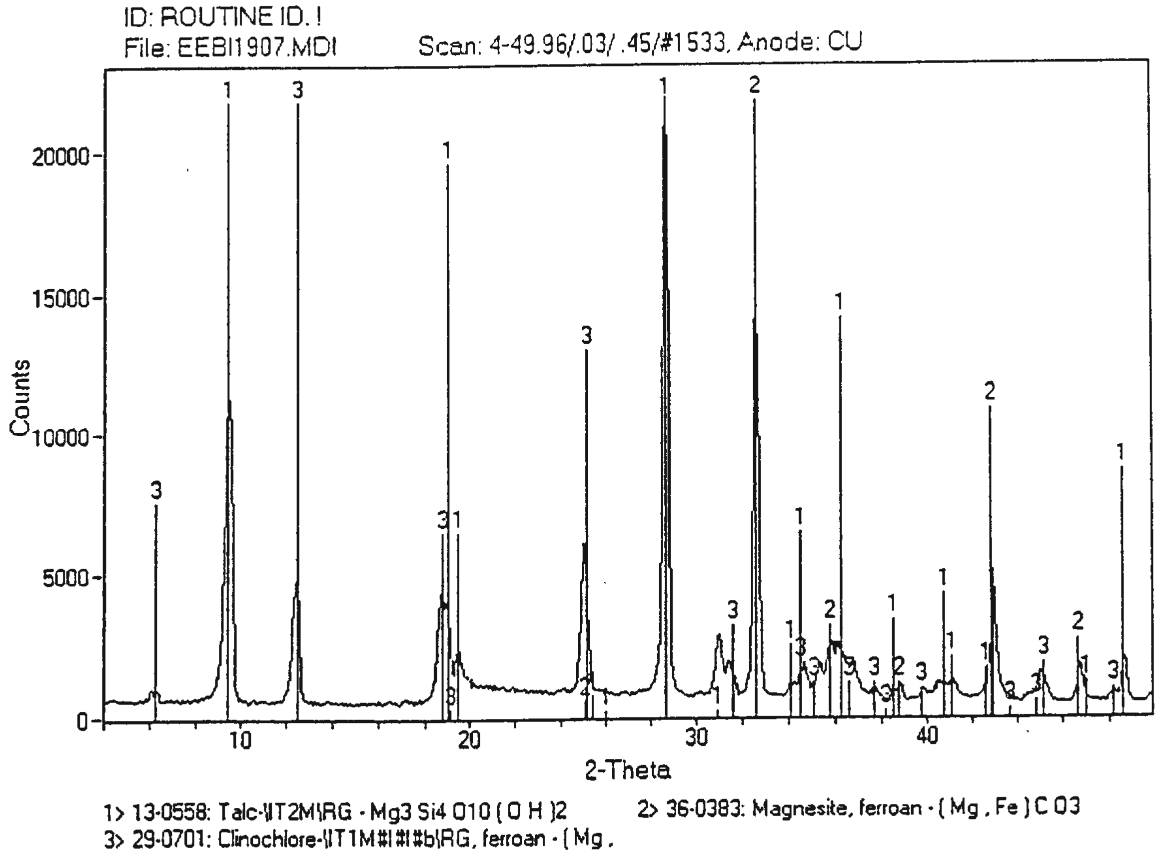
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1
3
1> 13-0558: Talc-\IT2M\RG - Mg3 Si4 O10 (O H)2
2> 36-0383: Magnesite, ferroan - (Mg , Fe) C O3
3> 29-0701: Clinochlore-\IT1M#I#I#b\RG, ferroan - (Mg ,

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-----------------------------------------------------------------------------

     Peak-Position  Centroid-Position   Peak & Area are without Bkgrd
     -------------- ---------------- -------------------------------
  #  2Theta     d     2Theta     d       Bkgrd   Peak    I%    Area    I%   FWHM*
-----------------------------------------------------------------------------
  1:  6.100 14.4762   6.105 14.4651     599     428   2.0     93   1.4  0.196
  2:  9.431  9.3705   9.419  9.3822     572   10677  50.5   4197  61.9  0.354
  3: 12.432  7.1144  12.430  7.1154     514    4259  20.1   1686  24.8  0.356
  4: 18.759  4.7267  18.760  4.7264     797    3623  17.1   1630  24.0  0.405
  5: 19.450  4.5601  19.451  4.5600     833    1494   7.1    888  13.1  0.535
  6: 25.002  3.5587  25.015  3.5569     869    5253  24.8   1882  27.7  0.322
  7: 28.632  3.1152  28.635  3.1149     770   21157 100.0   6785 100.0  0.289
  8: 30.911  2.8905  30.910  2.8906     740    2009   9.5    603   8.9  0.270
  9: 31.362  2.8500  31.362  2.8500     717    1225   5.8    575   8.5  0.422
 10: 32.563  2.7476  32.579  2.7463     767   14133  66.8   4089  60.3  0.260
 11: 34.055  2.6305  34.057  2.6304     832     352   1.7     53   0.8  0.136
 12: 34.571  2.5924  34.570  2.5925     937     734   3.5    231   3.4  0.283
 13: 35.771  2.5082  35.770  2.5082     806    1847   8.7    748  11.0  0.364
 14: 36.071  2.4880  36.070  2.4880     876    1640   7.8    673   9.9  0.369
 15: 37.749  2.3812  37.749  2.3812     848     172   0.8     10   0.1  0.052
 16: 38.829  2.3174  38.826  2.3176     592     524   2.5    112   1.7  0.192
 17: 39.822  2.2619  39.840  2.2609     607     435   2.1     71   1.0  0.147
 18: 41.112  2.1938  41.106  2.1941     627     646   3.1    285   4.2  0.397
 19: 42.940  2.1045  42.953  2.1039     576    4037  19.1   1525  22.5  0.340
 20: 45.101  2.0086  45.102  2.0086     487    1040   4.9    512   7.5  0.443
 21: 46.809  1.9392  46.802  1.9395     502    1314   6.2    409   6.0  0.280
 22: 48.700  1.8683  48.691  1.8686     499    1477   7.0    420   6.2  0.256
-----------------------------------------------------------------------------
  * Intensity values are based on total raw counts.
```

APPENDIX TWO

MAJOR AND TRACE ELEMENT ANALYSES

In this study, the rocks were collected from the sites of interest and crushed into powder to be analysed by XRF and ICP-MS. The weathered surfaces of the rocks were removed prior to crushing. A hydraulic press with tungsten carbide heads was used in the first step to produce sand-sized particles. An agate crushing bowl was then used in the pulveriser to reduce the sample to powder. The agate crushing bowl was cleaned and pretreated (i.e., crushed and thrown out) with each sample prior to powdering to minimise contamination; where there was sufficient sample.

X-Ray fluorescence (XRF)

Major elements were determined at Memorial University on pressed powder pellets using a Fisons/Applied Research laboratories model 8420+ sequential wavelength dispersion x-ray spectrometer. This method can analyse up to 80 elements simultaneously.

Elements within a rock sample react characteristically to x-ray emission and elements are quantified. To ensure precise and accurate data, five reference standards are simultaneously analysed during each set of unknown samples. The standards are used to accuratelycalibrate the instrument for element concentrations.

Loss on Ignition (LOI)

LOI is calculated for each of the samples prior to element analysis using XRF. This value, expressed in per cent, is determined by heating approximately 3 grams of sample (both sample and crucible weight were calculated) to 1050°C in pre-ignited disposable porcelain crucibles overnight to determine the amount of powder left after the loss of water-based mineral phases. Pressed pellets are then formed using the baked powder mixed with 0.42g of phenolic resin for binding. The rock powder and resin in a glass vial were combined on a roller mixer for approximately 10 minutes and then placed into a Herzog pellet press pressurised at 20 tons for approximately 5 seconds. The pressed powder pellet can be analysed for major and trace element abundances using the trace package. In this study, due to low trace element concentrations XRF was used for major element analysis only.

Inductively Coupled Plasma - Mass Spectrometry (ICP-MS)

ICP-MS is an analytical instrument that can measure the rare earth elements, more precisely than XRF, and is an essential tool in determining the source(s) of soapstone. The insturment used was a Hewlett Packard 4500 mass spectrometer at the Earth Sciences Department, MUN. Rock samples were acid-dissolved with pure nitric, hydrofluoric (HF) and hydrochloric acids (HCL), and then analysed. This dissolution process took approximately two weeks.

Contamination is a factor where concentrations of elements are less than 1ppm therefore it is essential to use very pure acids to reduce the risk of contamination. Double distilled nitric acid was used in place of the nitric acid typically used at the ICP-MS facility to ensure the samples were free of external contaminants.

Analytical precision, accuracy, and detection limits were evaluated to assess data reliability (Jenner 1996). The use of more than one technique and analysing for both major and trace elements ensures the acquisition of robust, reproducible data via comparison of analytes common to two techniques. Precision is measured through analytical reproducibility over time and through repeat samples in one run (Jenner 1996). Duplicate and triplicate samples were included in ICP-MS sample runs to determine precision (e.g., Fig.A2-1; Table A2.1). Precision is expressed as the relative standard deviation (RSD) from the average or mean element concentration.

Accuracy (or the correct value) of element concentrations in a sample is determined by comparing the measured concentration to the "true value" of that element and is expressed as the percentage difference (Jenner 1996). In this study, for the dunite standard DTS-1, the true values of the REEs are taken to be those of Jain et al. (2000), which are more recent than Govindaraju's 1989 published literature values (Table A2-1). Govindaraju's published values, particularly the HREEs Er, Tm, Yb, and Lu, exhibit a "saw-tooth" pattern (Fig. A2-1), satisfying the Oddo-Harkins rule, which states that if REE concentrations are plotted against atomic number then they will exhibit a jagged pattern (Potts 1987:430). REE abundances must therefore be normalised to either the composition of chondritic meteorites or the primitive mantle.

A dunite (DTS-1) is used as a reference standard for these analyses as the REE concentrations of DTS-1 are comparable to the samples in this study. It is possible to have confidence in the REE abundances of the artifact and outcrop samples due to the

Table A2-1: Comparison of dunite standard DTS-1 from four ICP runs with suggested values (ppm) based on Jain et al. (2000). b.d. = numbers below analytical detection limits; Avg = Average; Std = standard deviation; RSD = relative standard deviation; MPV = most probable value

	RUN	Th	Nb	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Avg LOD		0.002	0.003	0.009	0.012	0.009	0.011	0.012	0.008	0.009	0.008	0.021	0.008	0.017	0.008	0.009	0.003
DTS-1	773	0.011	0.015	0.034	0.055	0.009	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.006	b.d.	0.009	b.d.
DTS-1 REP	773	0.011	0.014	0.032	0.053	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.009	b.d.
DTS-1	783	0.011	0.018	0.032	0.055	0.007	0.025	0.004	b.d.	0.003	0.001	0.005	0.001	0.006	0.002	0.010	0.002
DTS-1	787	0.016	0.019	0.026	0.049	b.d.	0.021	0.003	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.002
DTS-1-30	788	0.014	0.021	0.028	0.053	b.d.	0.021	0.004	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.002
DTS-1-55	838	0.097	0.017	0.026	0.056	0.006	0.026	b.d.	b.d.	0.004	b.d.	0.004	0.001	0.004	b.d.	0.009	0.002
DTS-1 X5	838	0.023	0.016	0.025	0.052	0.007	0.030	b.d.	b.d.	0.003	b.d.	0.003	0.001	0.005	0.002	0.008	0.001
Avg		0.026	0.017	0.029	0.053	0.007	0.025	0.004		0.003	0.001	0.004	0.001	0.005	0.002	0.009	0.002
Std		0.029	0.002	0.003	0.002	0.001	0.003	0.000		0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000
RSD*				**0.128**	**0.127**	**0.038**	**0.063**	**0.065**		**0.129**		**0.245**	**0.000**	**0.207**	**0.000**	**0.120**	**0.200**
MPV+				0.025	0.053	0.006	0.024	0.004	0.001	0.004	0.001	0.004	0.001	0.005	0.001	0.009	0.002
Avg/ MPV (%)				**1.160**	**1.005**	**1.208**	**1.025**	**0.917**		**0.833**	**1.000**	**1.000**	**1.000**	**1.050**	**2.000**	**1.000**	**0.900**

*RSD = Std/Avg

+values of Jain et al. (2000).

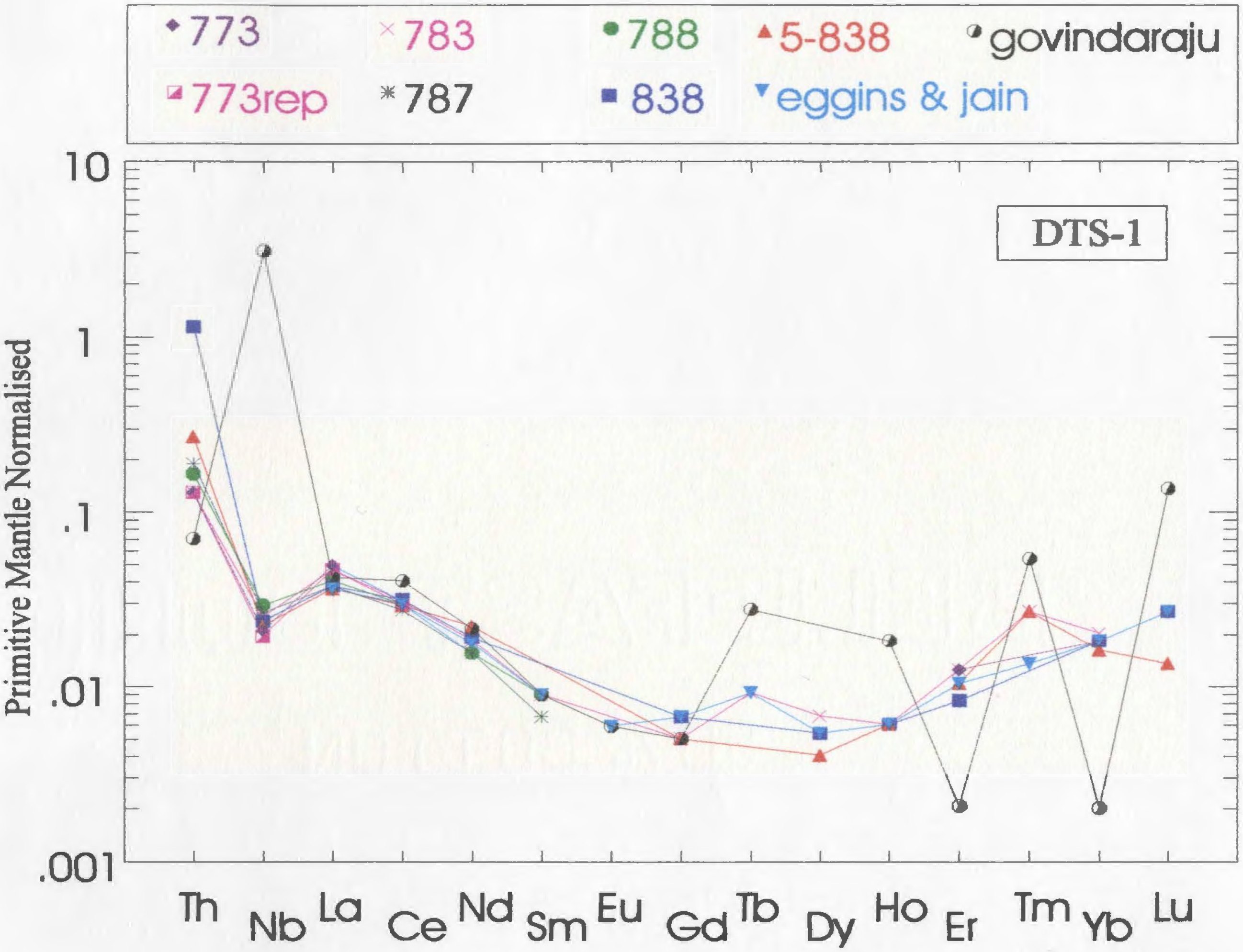


Figure A2-1 : Precision of the Dunite standard DTS-1 from five different ICP-MS runs (773, 783, 787, 788, 838) as compared to most probable values as defined by Govindaraju 1989, and average values of Eggins et al. (1997) and Jain et al. (2000). Sample 773rep is a DTS-1 sample repeat in the 773 run and 5-838 is DTS-1 at 5 times normal concentration in run 838. Elements below analytical detection limits are not plotted.

reproducibility and accuracy attained using ICP-MS for DTS-1 (Fig. A2-1). The accuracy is stated as average concentration divided by the most probable value for that element (AVG/MPV in Table A2-1). The values closest to one indicate the best accuracy and these include Tb, Dy, Ho, Yb, and Lu while Ce, Nd, Sm, and Er are close to one.

ICP-MS Limit of Detection (LOD) Considerations

For the analysis of samples with low elemental concentrations, low analytical LODs are crucial to REE abundance determinations. The LOD is calculated as 3 times the standard deviation of the concentration of an element, represented in oxide percent for major elements and in ppm for trace elements. Instrumental neutron activation analysis has typically been used by archaeologists to determine the source of soapstone artifacts (Nagle 1984; Allen and Pennell; Moffat and Buttler 1986). It is apparent from Table A that current determinations by ICP-MS surpass INAA capabilities in having lower limits of detection as well as in the ability to detect abundances of a wider range of trace elements. Further, current detection limitations at MUN ICP-MS facilities have improved by an order of magnitude since 1990. Despite this analytical progress, element concentrations in REE depleted rocks like soapstone combined with LREE mobility continue to present challenges when studying fluid altered ultramafic rocks.

Table A2-2: Trace elements and their detection limits (in ppm) for ICP-MS (Jenner 1990) and for this study (i.e. 2000 analysis) as compared to INAA analysis (Potts 1987), which has been typically used for soapstone artifact provenancing studies.

	La	**Ce**	**Pr**	**Nd**	**Sm**	**Eu**	**Gd**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**
INAA[1]	5	2.1		4.6	0.1	0.05	4.6	0.09		1.7		0.34
ICP-MS[2] **(1990)**	0.01	0.01	0.01	0.04	0.03	0.01	0.03	.006	0.02	.006	0.02	0.07
ICP- MS[3] **(2000)**	.002	.003	.002	.003	.003	.002	.002	.001	.004	.001	.003	.001

	Yb	**Lu**	**Nb**	**Ta**	**Zr**	**Hf**	**Th**	**U**	**Pb**	**Rb**	**Sr**	**Y**
INAA	0.14	0.10		0.07	100	0.20	0.2	0.05		10		
ICP-MS (1990)	0.02	.006	0.02	.004	0.05	0.02	0.01	0.01	0.07	0.12	0.20	0.01
ICP-MS (2000)	.002	.001	.0004	.0001	.011	.002	.0003	.002	.024	.047	.12	.003

ICP-MS Procedure (from Lakmali Hewa: pers.comm)

A run of samples on the ICP-MS consists of 24 samples. This includes 1 acid blank, DNC-1, MRG-1, 3 procedure duplicates (repeat dissolution of another sample in the run) and 18 samples. Preparation steps are as follows:

1) 24 clean and dry teflon screw cap jars are labelled on jar and cover.

2) 0.1000g of powder sample is measured into each jar.

3) 2ml of 8N HNO_3 (normal double distilled nitric acid) is added and swirled, 1 ml of HF is then added and cover is replaced

4) Samples are refluxed overnight

---

1 - Values from Potts (1987) Instrumental Neutron Activation Analysis (cf. Jenner 1996). These are the best possible values for INAA.

2 - From Jenner et al. (1990) acid digestion. 3 sigma detection limits. Best values obtained from MUN ICP-MS.

3 - Results from this study MUN (ICP-MS MUN values obtained in 2000). 3 sigma detection limits. These are the best values obtained in all runs.

5) Samples are checked for complete dissolution – if not dissolved they are left for another day. If dissolved, cover is removed carefully and rinsed into the jar with a few mls of 8N HNO_3. Samples are evaporated at 80-100°C until dry.

6) Jars are cooled and another 1 ml of HF and 2 ml of 8N HNO_3 are added. Samples are refluxed for 2-3 days (or as long as necessary) to ensure complete dissolution of minerals (e.g. zircon).

7) Covers are removed and rinsed as before and left to evaporate.

8) 2 ml 8N HNO_3 and 1 ml boric acid (5000ppm B) are added and sample is left to evaporate.

9) Add 2 ml and evaporate. Repeat.

10) 2ml 8N HNO_3 are added and covers are replaced and warmed gently to get all residue in solution.

11) Rinse covers into jars with Nanopure water.

12) Transfer samples to clean, dry and labelled bottles, rinse jars into bottles, add 0.665ml of oxalic acid, 0.330ml boric acid/HF solution and makeup to a final weight of 30g with Nanopure water.

13) Samples are spiked with a known spike solution before running on the ICP-MS. 2 test tubes are labelled, 1 spiked and one unspiked. Into the spiked tube 5g of spike solution is accurately weighed, 1g of sample solution and 4g of 0.2N HNO_3. Into the unspiked tube, 9g of 0.2N HNO_3 and 1g of sample solution are accurately weighed.

Table A2-3: Concentrations for each sample by individual Run

RUN	Sample Name	Sample Weight	Final Volume	Sample Solution Weight	0.2N Weight	Spike Weight
838	TROUT-1	0.1096	30.83	1.0599	9.3499	N/A
				1.0863	4.1816	5.0367
	TROUT-2	0.1016	30.42	1.5600	9.2248	N/A
				1.6092	4.0815	5.0555
	TABLE-1	0.1065	30.42	1.4487	9.1571	N/A
				1.2918	4.1003	5.0280
	TABLE-2	0.1054	30.14	1.6376	9.1415	N/A
				1.6851	4.0271	5.0540
	TABLE-2*	0.1025	30.92	1.2701	9.6016	N/A
				1.1191	4.1645	5.0288
	TROUT-1X5	0.1096	30.83	2.5183	7.7952	N/A
				2.7885	2.6746	5.0577
	TROUT-2X5	0.1016	30.42	2.5847	7.6229	N/A
				2.6260	2.6173	5.0339
	TABLE-1X5	0.1065	30.42	2.6801	7.5741	N/A
				2.7693	2.8412	5.0331
	TABLE-2X5	0.1054	30.14	2.4927	7.4246	N/A
				2.7247	3.1063	5.0392
	TABLE-2*X5	0.1025	30.92	2.5487	7.6012	N/A
				2.4851	2.4756	5.0293
782	Fdl2	0.1000	60.00	0.5000	9.5000	N/A
	Fdl2s			0.5000	4.5000	5.0000
	Fdl3	0.1000	60.00	0.5000	9.5000	N/A
	Fdl3s			0.5000	4.5000	5.0000
	Fdl4	0.1000	60.00	0.5000	9.5000	N/A
	Fdl4s			0.5000	4.5000	5.0000
	Fdl5	0.1174	30.10	4.8969	4.9934	N/A
	Fdl5s			5.4117	0.0000	5.0740
	C1	0.1185	30.46	5.0116	5.0073	
	C1s			5.2103	0.0000	5.0725
	C762	0.1069	30.14	5.2326	5.0138	
	C762s			5.0060	0.0000	5.0582
	C2044	0.1145	30.23	5.0067	5.4521	
	C2044s			5.2019	0.0000	5.0699
	C2896	0.1006	30.12	5.2710	5.0495	
	C2896s			5.0177	0.0000	5.0670
	C3952	0.1039	30.74	5.3477	5.0473	
	C3952s			5.2478	0.0000	5.0743
	C19078	0.1069	30.51	5.2144	5.0016	
	C19078s			5.1918	0.0000	5.0721
	C19078*	0.1161	30.13	5.1969	5.1146	
	C19078*s			5.1640	0.0000	5.0683
	Fdl2*	0.1013	30.19	5.0399	5.1277	
	Fdl2*s			4.9853	0.0000	5.0628
	Anth1	0.1117	60.04	0.5833	9.7048	

	Anth1s			0.5726	4.4845	5.0728
	Anth1*	0.1117	60.04	2.4656	7.5220	
	Anth1*s			2.6320	2.5490	5.0612
	Anth1**	0.1117	60.04	4.9601	5.2746	
	Anth1**s			5.2447	0.0000	5.0778
	Anth3	0.1180	60.07	0.5750	9.5316	
	Anth3s			0.5652	4.5975	5.0099
	Anth3*	0.1180	60.07	2.4533	7.8123	
	Anth3*s			2.6030	2.5705	5.0528
	Anth3**	0.1180	60.07	5.0709	5.4221	
	Anth3**s			5.4558	0.0000	5.2917
	Co981	0.1009	60.29	0.5640	9.4819	
	Co981s			0.5702	4.3442	5.1824
	Co981*	0.1009	60.29	2.6192	7.4263	
	Co981*s			2.6849	2.4198	5.0567
	Co981**	0.1009	60.29	5.1365	5.0079	
	Co981**s			5.4126	0.0000	5.1992

Due to low rare earth element abundances in these soapstones of harzburgitic and peridotite origin, rock powder sample size for ICP-MS was increased from 0.1g to 0.8g (Fig. A2-2). This more concentrated solution intensified the amount of the rare earth elements in each of the samples. This placed most of the trace element concentrations above the instruments detection limits by approximately an order of magnitude.

Geological Reference Materials

Geological reference materials are mainly used for the calibration of analytical techniques or to validate geochemical data. The United States Geological Survey (USGS) provides the accepted samples used for standards. The two main reference standards used for this study are DTS-1, a dunite, and PCC-1, a peridotite. These rocks have low REE concentrations and are most useful for comparison with soapstones.

Elemental concentrations were determined by XRF and ICP-MS and then transferred from Lotus 1-2-3 spreadsheets to the element software programme NEWPET. Once in NEWPET, elements could be plotted graphically to assign groupings and to identify REE patterns. Following this, particular REE patterns could be used to identify geological fingerprints of outcrop samples.

NEWPET configuration settings:

- Anhydrous
- Iron recalulation: 1

For the primitive mantle normalised plots, elements were divided by the measured values for that element in the primitive mantle, presented in the table below. This allows the representative REE geochemistry to be presented, that is, without the effects of the even-odd atomic numbers of the REEs.

Once plots were generated in NEWPET they were imported to CorelDraw 6 for editing.

Element	**Normalised value**
La	0.687
Sm	0.444
Gd	0.596
Dy	0.737
Yb	0.493
Lu	0.074

APPENDIX THREE

Geological Timescale

Era	Period	Commencement age (millions of years)
Cenozoic	Quaternary	2
	Tertiary	65
Mesozoic	Cretaceous	130
	Jurassic	205
	Triassic	245
Paleozoic	Permian	290
	Carboniferous	360
	Devonian	400
	Silurian	420
	Ordovician	495
	Cambrian	530
Precambrian	*Proterozoic* Hadrinian	1000
	Proterozoic Helikian	1800
	Proterozoic Aphebian	2500
	Archean	4600

APPENDIX FOUR

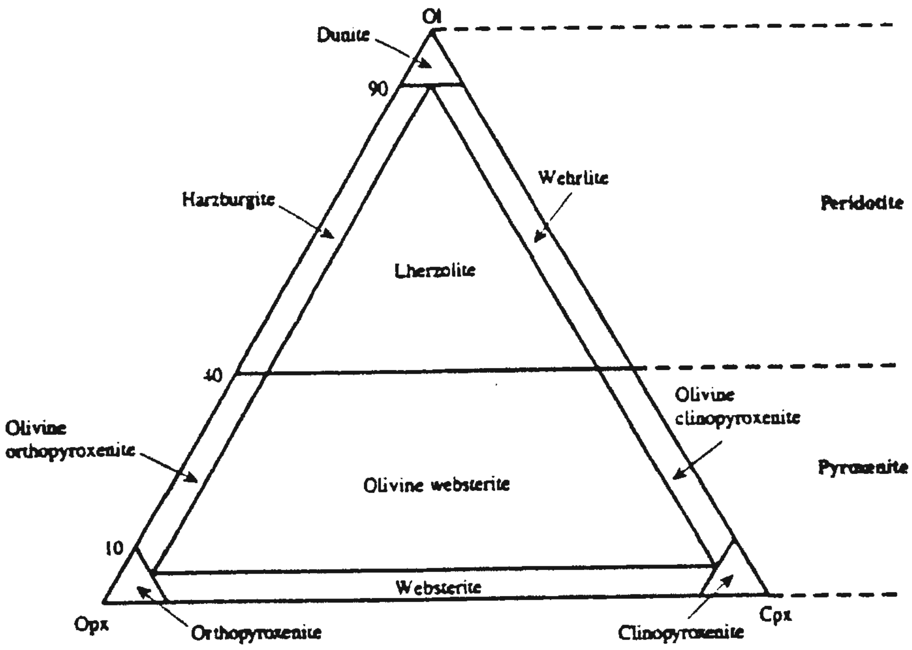
GLOSSARY OF TERMS (after Bates and Jackson 1984)

Anhedral: Refers to the shape of a crystal that lacks any characteristic faces

Dunite: A peridotite consisting essentially of olivine, with accessory pyroxene, plagioclase, or chromite

Harzburgite: A peridotite composed of primarily of minerals olivine and orthopyroxene

IUGS Classification for Ultramafic Rocks (LeMaitre 1989):



Ol: Olivine; Opx: orthopyroxene; Cpx: clinopyroxene.

Metamorphism: The mineralogical, chemical, and structural adjustment of solid rocks to physical and chemical conditions imposed at depth below the surface zones of weathering and cementation, which differ from the conditions under which rocks originated.

Ophiolite: An assemblage of mafic and ultramafic igneous rocks ranging from spilite and basalt to gabbro and peridotite, including rocks rich in serpentine, chlorite, epidote, and albite derived from them by later metamorphism.

Peridotite: A coarse grained plutonic rock consisting mainly of olivine, with or without other mafic minerals such as pyroxenes, amphiboles, or micas.

Protolith: parent rock assemblage

Pyroxenite: An ultramafic plutonic rock mainly composed of pyroxene, with accessory hornblende, biotite, or olivine

Soapstone (also known as steatite): A metamorphic rock composed mainly of talc, with varying amounts of other minerals (e.g., serpentine, magnesite)

Spinel: A mineral, $MgAl_2O_4$

Subhedral: Refers to a crystal that is bounded by only some of its characteristic faces

Thin sections: 30-micron thick rock slices glued to a microscope slide; used for mineral identification

Ultramafic: An igneous rock consisting of mafic minerals